SIMULATION AND PERFORMANCE EVALUATION OF LOW AND HIGH POWER ACTIVE POWER FILTERS

By

Manoj Kumar Thakur

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

AUGUST, 2003

SIMULATION AND PERFORMANCE EVALUATION OF LOW AND HIGH POWER ACTIVE POWER FILTERS

A thesis submitted
in partial fulfillment of the requirements
For the degree of

Master of Technology

by

Manoj Kumar Thakur

Department of Electrical Engineering
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR
August, 2003

CERTIFICATE

This is certified that the work contained in this thesis entitled "**Simulation and Performance Evaluation of Low and High Power Active Power Filters**", by Manoj Kumar Thakur, has been carried out under our supervision and that this work has not been submitted elsewhere for any degree.

04/8/03

Dr. S.P.Das
Assistant Professor
Department of Electrical Engg.
Indian Institute of Technology
Kanpur

Dr. Gopal K. Dubey
Professor
Department of Electrical Engg.
Indian Institute of Technology
Kanpur

Active power filters (APF) are widely used in distribution systems for VAR compensation and harmonic filtering. In this thesis, models of Active Power Filter have been developed for single-phase, three-phase three-wire and three-phase four-wire systems for compensation of single-phase, three-phase balanced and unbalanced loads. Both non-linear and inductive linear loads have been considered for each topology of APF. Proportional Integral (PI) controller has been used in each control scheme. PI controller employs control over the average dc bus capacitor voltage of the active filter and maintains it at the reference voltage. It also generates the reference supply currents to draw the necessary power from the ac source to feed the real power required by the load in addition to the real power required to meet the Active Power Filter losses. A hysteresis based bang bang current control is employed for fast and efficient control. Simulation of each type of APF has been done for different loads with the help of SABER simulator for steady state and dynamic performance evaluation.

A parallel converter based APF suitable for high power load compensation has been proposed. SABER simulation has been done for the parallel converter topology with linear and non-linear loads. The parallel converter is a combination of two converters, having high power low frequency devices (main converter) and low power high frequency devices (auxiliary converter). A neutral point clamped (NPC) converter acts as the main converter for VAR compensation of the load. The main converter harmonics and load harmonic current are compensated by the parallel connected auxiliary converter operating at low power and high frequency.

Key words: Single phase APF, Three phase APF, Three phase three wire system, Three phase four wire system, Neutral Point Clamped (NPC) converter, Parallel Converter, SABER Simulator.

Acknowledgement

It is a privilege to work under the guidance of Prof. G. K. Dubey who has always motivated me to think with audacity and to create humbly with perseverance. His exceptional capability of reducing complexities to simpler forms has enormously helped in the smooth progress of the work. It is an enlightening experience to learn and create under his caring attitude. With sincerity and honesty I express my profound sense of gratitude and indebtedness to my teacher and supervisor.

To work under the supervision of Dr. S. P. Das has been an extremely fruitful and motivating experience. His instantaneous problem solving capability has enormously helped in speeding up the work. His rich experience, exemplary patience, concern and understanding has resulted in completion of this work to my fullest satisfaction. Full heartedly I express my strong sense of gratitude and indebtedness to my supervisor.

I want to express my sincere thanks to my teachers Prof. S.R.Doradla, Prof. Arindam Ghosh, Prof. A. Joshi, It has been a great pleasure to study in their association.

I sincerely thank my friend Pankaj Jaiswal for his continuous cooperation throughout this work. I sincerely thank my friends Shahab, Om Prakash Dwivedi, Umakant Dhar Dwivedi, Auddy ,Ranjan, Srinivasulu for their timely help and cooperation.

I want to express my thanks to Pankaj Meena, Amit Jindal, Nath Sir and many others who made my stay at IIT memorable in my life.

The thesis wouldn't have been completed without the active participation of our technical staff. I am very much thankful to Mr. O.P. Arora, Mr. Nitin Chourasia, Mr. Amit Basu and many others.

Finally I would like to express my thanks to all those who helped me directly or indirectly in the progress and completion of this work.

Manoj

CONTENTS

List of Figures

CHAPTER 1

INTRODUCTION

1.1 General

The continuous increase in demand of electricity and lack in its availability have forced power engineers to define, study and derive methods for the effective utilization of ac supply system Phase-wise unbalanced reactive power demand in power system is due to substantial single-phase loads, and large fluctuating industrial and domestic loads, such as lighting, welding, heating, commercial building air conditioning, domestics appliances, electric arc furnaces, rolling mills, traction and small process industries, etc These loads cause system unbalance and lead to wide fluctuations in the supply voltages Such supply system can not be used to feed sensitive loads like computers, electronic equipments, etc On the other hand, the presence of unbalance loads results in reactive power burden and excessive neutral current, which causes low system efficiency, poor power factor and inadequate utilization of distribution system Moreover, solid-state control of ac power using thyristors and other semiconductor devices is being used increasingly to feed a number of electrical loads, such as adjustable speed drives, computer power supply, etc These electrical loads draw harmonics and reactive power components of current from ac mains and act as non-linear loads In three-phase systems, such loads also create unbalance and excessive neutral current These unwanted features cause well known adverse effects like additional heating, over voltages (due to resonance condition) in the

distribution system, voltage distortions errors in metering, malfunctioning of relays, and interference with communication and control equipment

Therefore, the power quality has become an important issue Many definitions of power quality are available in the literature One possible definition of electric power quality relates to whether loads are properly served

1.2 Concepts for Reactive Power Compensation, Load Balancing, Harmonics Elimination and Neutral Current Compensation

In this section, the importance of load compensation is highlighted Load compensation is basically the management of power to improve the quality of supply in ac power systems The term load compensation is used where the power management is affected for a single load The compensating equipments are usually installed on the consumer's own premises near to load Load compensation has following four main objectives

(1) Reactive power compensation

(2) Load balancing

(3) Harmonics elimination

(4) Neutral current compensation

1.2.1 Reactive power compensation

Reactive power compensation usually means the practice of generating reactive power as close as possible to the load which requires it, rather than supplying it from a remote power station Most industrial loads have lagging power factors and they absorb reactive power The load current therefore tends to be larger than required to supply the real power alone Only the real power is ultimately useful in energy conversion and excess

load current represents a waste to the consumer, who has to pay not only for the excess power, but also for the excess losses produced in the supply cables The supply utilities have also good reasons for not transmitting unnecessary reactive power from generators to the loads Their generators and distribution networks can not be used at full capacity

1.2.2 Load balancing

The second objective in the load compensation is load balancing Most ac power systems are three-phase and designed for balanced operation Unbalanced operation gives rise to unbalanced currents in the supply system In a three phase four wire system, current in the neutral is expected to be small, typically not more than 40%-50% of normal phase currents However, excessive neutral current phenomenon arises, especially in unbalanced circuits such as fluorescent lighting loads, computer loads, etc The excessive neutral current can potentially affect both the neutral conductor and the transformer to which it is connected Unbalanced currents would have undesirable effects, including additional losses in motors and generating units, oscillating torque in ac machines, increased ripple in rectifiers, malfunction of several types of equipment and saturation of transformers

1.2.3 Harmonic elimination

A harmonic can be defined as "a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency" Non-linear loads such as computers, electronic-ballast lighting systems in commercial buildings and variable speed drives draw current in short spurt framed by 50Hz sine wave Such abrupt current changes distort the supply voltage Power system problems such as communication interference, heating and solid state devices malfunction are the direct

result of harmonics Other effects of harmonics can be highlighted as follows (i) Since most ac equipments ratings are based on 50Hz losses, the addition of harmonic loss components require derating of the equipment (ii) It can cause the solid state device to malfunction if the equipment is sensitive to zero crossing (iii) Magnetic coupling can result between electrical power circuits and communication interference Distortion from harmonics is quantified in terms of a distortion factor

1.2.4 Neutral current compensation

Some of the harmonic frequencies produced by balanced single-phase non-linear loads in three-phase system, may reinforce each other in the neutral line producing substantial current which may exceed the rating of the neutral conductor and result in overheating and neutral conductor burn out In an unbalance system, neutral current phenomenon leads to the presence of negative sequence components also, along with zero sequence components

1.3 State-of-the-Art

This section presents the state-of-the-art on load compensation technology It is sectionalized on the basis of passive or active components used for load compensation

1.3.1 Use of passive component for load compensation

In the industries, where normally the cost is a major consideration and loads are generally of fixed static type, the use of passive components is recommended for reactive power compensation, harmonics elimination and load balancing Use of passive filter may be a likely solution with an affordable price, for the filtering of low order current harmonic

frequencies However, the performance of passive filter depends on load and system characteristics

1.3.2 Use of active components for load compensation

While compensating continuously varying loads present in the varying system parameter environment, passive filter may not provide desirable compensation In such cases, recently developed active power filters are considered more appropriate The concept of active power filters has been introduced a long back, but its utility in practical system has become feasible only after the tremendous improvement in the semiconductor device technology, thus providing better, reliable and more economical systems Moreover, a number of control methods in single-phase, three-phase three-wire, and three-phase four-wire systems are reported for the improved performance of active power filter A gradual refinement in active power filter technology can be observed in terms of fast response, improved transient performance, optimum selection of energy storage components and reduction in the rating of active power filter

1.3.3 Development of control methods

Control methods for active power filters can be employed either in frequency domain or in time domain Correction in frequency domain is accomplished by using either predetermined harmonic injection method or by including periodic characteristics of the distorted waveform Its disadvantage lies in the enormous computational requirements needed for a solution, which results in longer time delay Time domain methods are based on the use of instantaneous voltage or current signals, or averaging them over a small time The main advantage of time domain correction is its fast response to changes in the supply system or in the load

1.3.4 Load compensator providing discrete control

Dealing with fixed static loads, the compensation is generally achieved by using passive components However, in the event of varying load, switching devices controlled passive device may give a discrete control over compensating action Various types of compensator are identified for realizing variable reactances (required for load balancing and reactive power compensation) by saturable reactor, thyristor controlled reactor (TCR), thyristor switched capacitor (TSC) or by combination of TCR and TSC Saturable reactor compensator was the first type of compensator to be developed and applied successfully in the power system It consists of a saturated reactor and a fixed capacitor bank But this has limited flexibility with regard to modification of its characteristics and is thus less adaptable to changing system condition as compared to thyristor controlled reactors or capacitors Thyristor controlled reactor compensator consists of six-pulse or twelve pulse thyristor controlled reactors with a fixed shunt capacitor bank The thyristor switched capacitor compensator consists of a thyristor switched capacitor bank which is split into a number of binary weighted units to achieve a step-wise control In the practical configuration, a reactor is also applied to reduce the rate of change of inrush current through shunt capacitor

The combination of TCR and TSC gives a smoothening effect to the step-wise variation of the TCR or TSC separately The TCR/TSC compensators have low operation losses as the rating of the smoothening reactor is smaller than the rating of reactors applied in other TCR static compensators Such compensators are often know as static compensators, and are able to deal with reactive power and load balancing problems effectively However,

these compensators do not provide current harmonics elimination, on the contrary they introduce harmonics in the supply system

1 3.5 Load compensator providing continuous control

With the proliferation of more varying linear /non-linear unbalanced reactive type of loads, it has become imperative to realize the concept of active power filter, so as to provide a dynamic and adjustable solution to improve the power quality Mainly, two types of converters either voltage source inverter (VSI) or current source inverter (CSI) can be used as an active power filter So far a clear trend for a preferred type of active power filter either VSI or CSI has not been identified in the literature The choice depends on source of distortion, equipment cost and amount of correction desired CSI type converters are considered to be sufficiently reliable but suffer from the disadvantages of higher losses and higher values of parallel ac power capacitors VSI types of converters have several advantages They are lighter, less expensive and can be readily connected in parallel or series to increase their combined rating Their combined switching rate can also be increased without increasing individual switching rates Hence, the present trend is to use a voltage source converter in the network for wide compensation, so that effectively the rating and switching frequency can be effectively increased

Apart from the advantages offered by voltage source converters, the performance of the APF greatly improves if it is capable of tracking the reference currents as closely as possible VSI operated in the current controlled mode exhibits higher level of dynamic performance since the output current of the converter is not subjected to delay caused by non-linear electrical circuit of the load Voltage source inverter can be controlled to

realize either ideal supply currents or ideal APF currents Control over supply currents may cause APF overloading in the event of sudden load disruptions So in view of this, control over APF current is employed using hysteresis based current control Considering these points, current controlled voltage source inverters are used as APFs in this thesis (Chapter-2 – Chapter-4)

1.4 Literature Review

Single-phase active power filters are reported by many authors in various types, such as shunt active power filter [3], series active power filter [4] and combination of series and shunt both [5]

Moran et al [10] have proposed use of three-phase three-wire PWM voltage source inverters operating at different switching frequency compensating for specific current harmonic components of non-linear load This way, PWM inverter operating at lowest switching frequency, compensates low frequency current harmonics Thus the second PWM inverter operating at medium switching frequency compensates medium switching load current harmonics and the third PWM inverter operating at high switching frequency compensates for high frequency current harmonics present The voltage source inverter operating at the lowest switching frequency is designed with the highest rated power

Furuhashi et al [14] and Chen et al [15] have utilized full bridge three-phase topology as an active power filter for three phase four wire system It consists of three independent single-phase full bridge voltage source inverters with a common dc bus and requires three single-phase transformers or a three-phase transformer with access to individual windings The primary side windings of three single-phase transformers are connected in

star, and path to neutral current is provided by connecting supply neutral to the star point of the primary transformer windings

1.5 Organization of the Thesis

Chapter 1- In this chapter an overview of degrading power quality and importance of compensators in the power system are given Some significant gaps in different aspects of compensation are identified.

Chapter 2- This chapter starts with the basic configuration of a single-phase active power filter and leads to the mathematical modeling of the system, active power filter and different linear and non-linear loads The control technique and the system are simulated to investigate the performance of the APF model

Chapter 3- In this chapter, a work pertaining to the steady state and transient analysis of a three-phase three-wire active power filter is examined The theoretical basis of the control scheme in light of three-phase three-wire system is discussed The mathematical models of three-phase three-wire system compatible active power filter and three-phase three-wire balanced/ unbalanced and linear/ non-linear loads are developed for simulation with SABER simulator

Chapter 4- This chapter examines the load compensation in a three-phase, four-wire distribution system Two configurations of active power filters are proposed and the topologies have been simulated for linear and non-linear loads

Chapter 5- This chapter presents a combination of parallel compensators, which have been shown to be useful for high power loads with large VAR and harmonics In the

proposed topology, the combination of high power low frequency devices and low power high frequency devices are utilized to their full capacity

Chapter 6 - This chapter presents the conclusions and suggestion for future work

CHAPTER 2

PERFORMANCE ANALYSIS OF ACTIVE POWER FILTER IN SINGLE-PHASE SYSTEM

2.1 General

The concept of reactive power compensation using passive components is already introduced in the preceding chapter However, compensation by passive elements is not advisable if the loads are time varying in nature Single-phase power conversion equipment required for rectifier fed variable speed drives, light control, temperature control, ac voltage regulators, SMPS, UPS, etc employ non-linear switching devices such as thyristors, diodes and triacs, which inject harmonics in to the ac mains Under such load conditions use of single-phase active power filter is advisable in the system This chapter presents simulation and performance analysis of single phase active power filter

2.2 Description of Single-phase System

A single-phase system consists of a single-phase active power filter (APF), its controller and load Fig 2 1 and Fig 2 2 show the basic power circuit of the system The active power filter is a conventional single-phase voltage source inverter using power electronic switch as switching devices, and a dc capacitor as an energy storage element It is connected in parallel with load and supply system In Fig 2 1, the ac mains is supplying a load comprising a single-phase diode bridge rectifier feeding a resistive-capacitive load Fig 2 2 shows a single-phase system feeding to a group of linear and nonlinear loads,

consisting of uncontrolled diode bridge rectifier feeding a resistive-capacitive load, an inductive load and an ac voltage controller feeding a resistive load

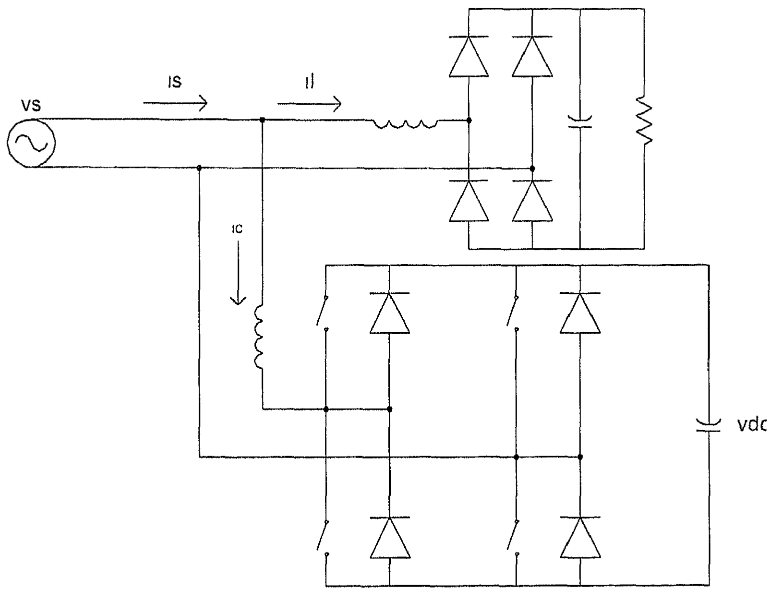

Fig 2 1 Single-phase active power filter

For compensation of loads, two loops are employed Firstly, the outer loop which generates the amplitude of reference supply current signal Depending upon the control scheme, voltage and current reference signals are fed to the controller The output of controller followed by a limiter (I_{sm}^*) decides the amplitude of reference supply current With the help of sensed input supply voltage, the instantaneous phase information is obtained By using the phase and amplitude signals, the instantaneous reference supply current (i_s^*) is derived in phase with the supply voltage for unity power factor current Instantaneous reference APF current (i_c^*) is computed by subtracting actual load current (i_l) from instantaneous reference supply current (i_s^*)

Secondly, the current control loop employs hysteresis current control over reference APF current (i^*_c) and actual APF current (i_c) to generate the gating pulses for APF switches This force APF current to follow the desired reference APF current signal generated by control technique

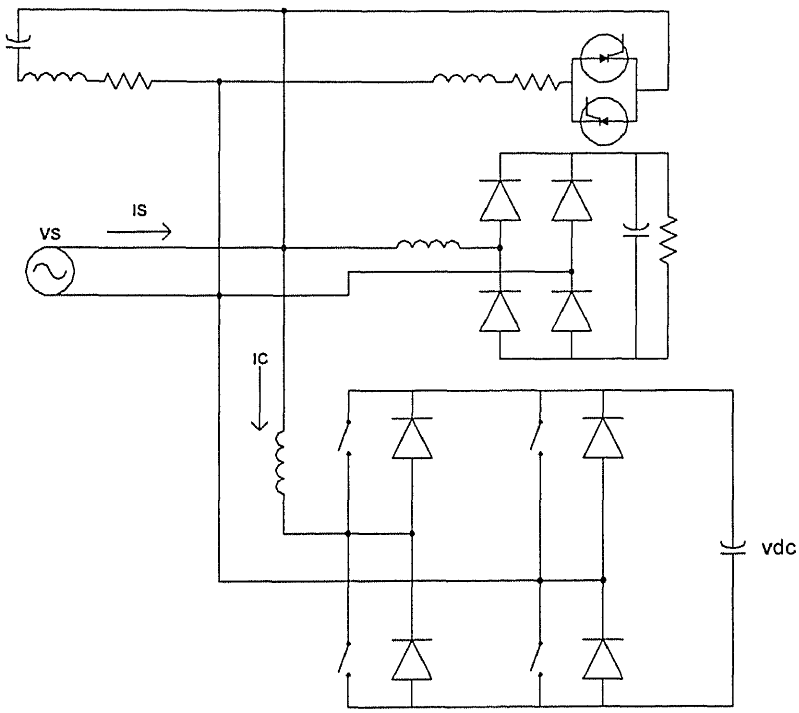

Fig 2 2 Single-phase active power filter with mixed loads

2.3 Proportional-integral Controller

The operation of PI controller is depicted in Fig 2 3 It can be explained by identifying flow of signals In this control scheme, the outer loop is a voltage control loop, which forces dc bus capacitor voltage of APF to stay in close proximity of the preset dc bus reference voltage

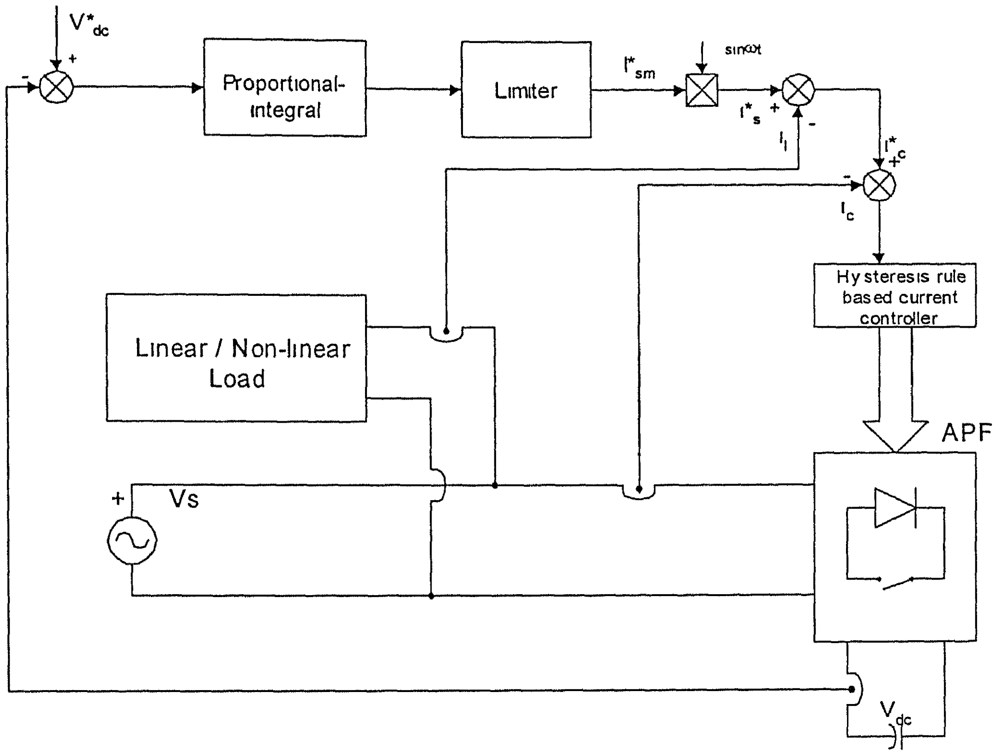

Fig 2 3 PI control scheme for single-phase APF

In single-phase APF, the voltage of the dc bus capacitor experiences second order harmonic ripples of ac mains fundamental frequency This voltage is averaged over the ripple period to be used as an input to the error detector Another input to the error detector is the preset dc bus reference capacitor voltage The error detector compares both the inputs and produces an output called voltage error The voltage error signal is then processed in the PI controller The output of the controller is then fed to a limiter The limiter puts a limit on output of the PI controller, and decides the maximum amplitude of the reference supply current

The action of the controller under steady state and transient state is described as follows

In steady-state, power supplied from the mains must be equal to the real power demanded by the load plus a small component of real power to feed switching losses and capacitor dielectric losses etc Hence, the average voltage of dc capacitor can be maintained at a

constant value If a power imbalance, such as transients caused by load change, occurs, the dc capacitor must supply power difference between mains and load in the transient state It results in voltage fluctuation of dc capacitor If real power supplied from the mains is smaller than that demanded by the load, the rest of the required power is supplied by the dc bus capacitor of the APF which causes reduction in average voltage of dc bus capacitor At this moment, amplitude of the mains current must be increased to increase the real power drawn from the mains

If the load on system reduces, the excess energy supplied by ac mains is absorbed by the dc bus capacitor of the APF It causes a rise in the dc bus capacitor voltage of APF The ac mains current must decrease to feed the new lower load requirements The limiter puts a limit on the amplitude of reference supply current or indirectly limits the maximum current supplied by active power filter Limit on amplitude of reference supply current is essential since during transients (such as load application) experienced by the system, the dc bus capacitor faces a large decrease in the stored energy of capacitor, resulting in large increase in the controller output The high value of reference supply current and thereby the reference APF current may even go beyond the rating of the active power filter components Moreover, large voltage variations on dc bus capacitor of APF reduce its life Therefore, in order to operate the active power filter with safe operating current, it becomes desirable to put a limit on the commend output of the controller Such a limit ensures that in no case the reference supply current will be allowed to jump more than the set value Both controller and limiter are parts of outer control loop of filter control structure

The output of this control loop generates the amplitude of reference supply current (I_{sm}^*) For the phase of reference supply current, unit current template (u(t)) is generated by sensing input supply voltage (v_s) using voltage sensor With the help of amplitude and phase information, an instantaneous reference supply current (i_s^*) is estimated Ideally, this current must be supplied by ac mains However, with self supporting dc bus, reference supply current signal consists of real power required by the load and another small component of real power is needed to replenish filter losses Instantaneous reference APF current (i_c^*) is computed from instantaneous reference supply current (i_s^*) and sensed load current (i_l)

For generating active power filter current such that it follows the reference APF currents, the inverter requires a particular type of ON/OFF pattern for its switches (which use power electronics switch with anti-parallel diode) This pattern is generated by employing hysteresis current controller The current comparator has a hysteresis band (hb) that determines permitted deviation of actual APF current from instantaneous reference APF current before inverter switching is initiated Depending upon hysteresis band, outer and inner envelopes of reference current are generated and actual current is allowed to move between two envelopes only Thus actual APF current tracks the reference current without significant amplitude error or phase delay

2.4 Mathematical Modelling of the System

Different parts of the system described in the section 2 3 are modelled separately A sequential mathematical modelling is carried out for the PI voltage controller

2.4 1 Supply system

Under normal operating conditions, supply system could be modelled as a sinusoidal voltage source of amplitude V_{sm} and frequency f Its instantaneous value can be expressed as

$$v_s(t)=V_{sm}\sin\omega t$$

Where $\omega=2*3.14*f$ electrical radians/second

$$u(t)=v_s(t)/V_{sm}=\sin\omega t$$

2 4 2 Proportional-Integral controller

The dc bus capacitor of active power filter is sensed using a voltage sensor and compared with set reference voltage (V_{dc}^*) The resulting voltage error $V_{e(n)}$ at nth sampling instant is expressed as

$$V_{e(n)}=V_{dc}^*-V_{dca(n)}$$

The output of PI voltage controller $V_{o(n)}$ at the nth sampling interval is expressed as

$$V_{o(n)}=V_{o(n-1)}+K_p\{V_{e(n)}-V_{e(n-1)}\}+K_iV_{e(n)}=I_{sm}^*$$

where K_p and K_i are proportional and integral gain constants of the voltage regulator $V_{(on)}$, $V_{o(n-1)}$ and $V_{(en)}$, $V_{e(n-1)}$ are the outputs of the controller and voltage errors at nth and (n-1)th sampling instant respectively The output $V_{o(n)}$ of the voltage controller is limited to a safe value and resulting limited output is taken as amplitude of the reference supply current I_{sm}^*

2 4.3 Reference supply current generation

The unit template u(t) obtained from sensed supply voltage is multiplied with the amplitude of reference source current I_{sm}^* The resulting signal as instantaneous reference supply current and given as

$Is(t)^* = I_{sm}{}^* u(t) = I_{sm}{}^* \sin\omega t$

2.4.4 Reference active power filter current estimation

Reference APF current (i_c^*) is computed by a using an error amplifier The difference between instantaneous reference supply current (i_s^*) and instantaneously sensed load current (i_l) must be supplied by APF So, the reference APF current is expressed as

$i_c^* = i_s^* - i_l$

2 4 5 Current controller

Hysteresis current control is employed over actual APF current (i_c) and reference APF current (i_c^*) It contributes to the switching pattern of APF devices

$i_c < (i_c^* - h_b)$ upper switch is OFF and lower switch is ON

$i_c > (i_c^* + h_b)$ upper switch is ON and lower switch is OFF

where h_b is hysteresis band of current controller

2.5 Simulation

In the previous section, all components of the system are modelled In this section the simulation of the system, has been made and the performance has been evaluated In the simulation process PI controller has been used and non-linear/inductive loads are taken The harmonic analysis of compensated supply current and load current is performed by using saber-scope and simulation has performed by using saber-sketch

Power circuit of single-phase active power filter is using in saber-sketch shown in Fig 2 4 and the control circuit modelling block diagram in SABER shown in Fig 2 5(a,b)

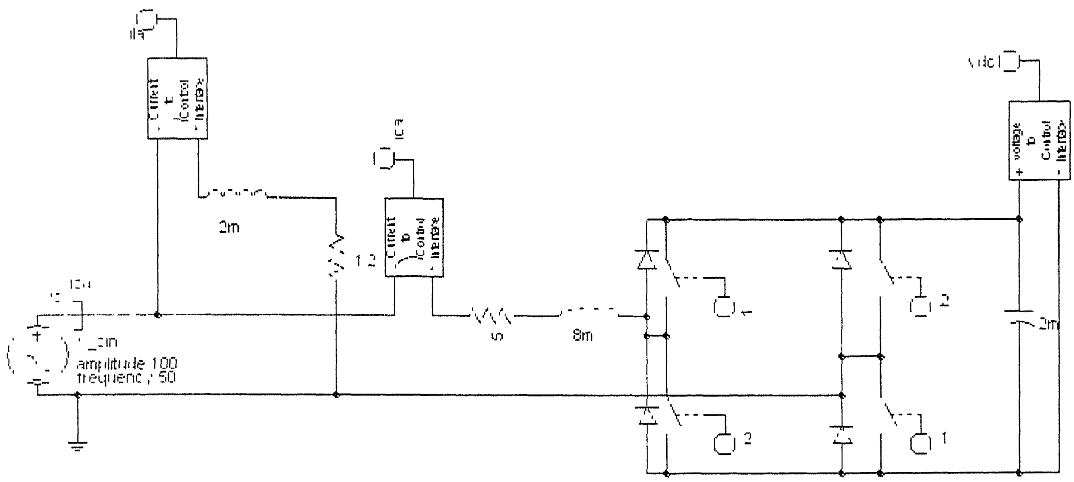

Fig. 2 5(a) Power circuit of single-phase APF

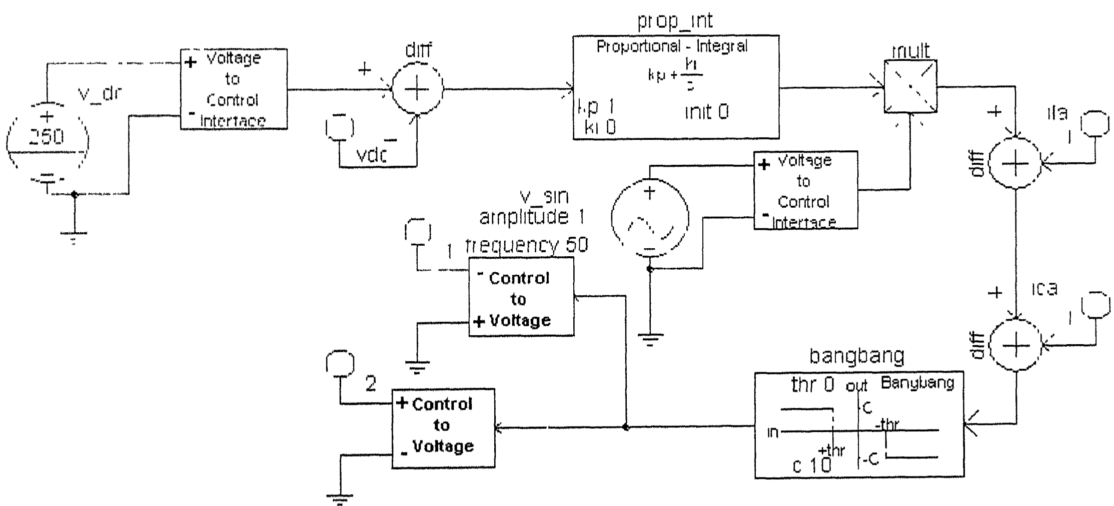

Fig. 2.5(b) Control circuit of single phase APF

2.6 Results and Discussion

Performance characteristics of the active power filter under various loading conditions are demonstrated in this section. Two types of loads are considered. The first one is a single-phase uncontrolled diode bridge rectifier feeding resistive-capacitive load and second is an inductive load.

2.6.1 Compensation of non-linear load

The compensation characteristics of the active power filter using a PI controller to compensate a single-phase diode bridge rectifier feeding a resistive-capacitive load is shown in Figs. 2.6-2.8. In Fig. 2.6, v_s is the ac main supply voltage, i_s is the compensated supply current. i_l is the load current. The active power filter current, i_c, and the dc capacitor voltage V_{dc} are shown in Fig. 2.7. Harmonic spectrum of load and source currents are shown in Fig. 2.8. It can be seen there by the APF we can compensate from THD=33.8% up to THD=4%.

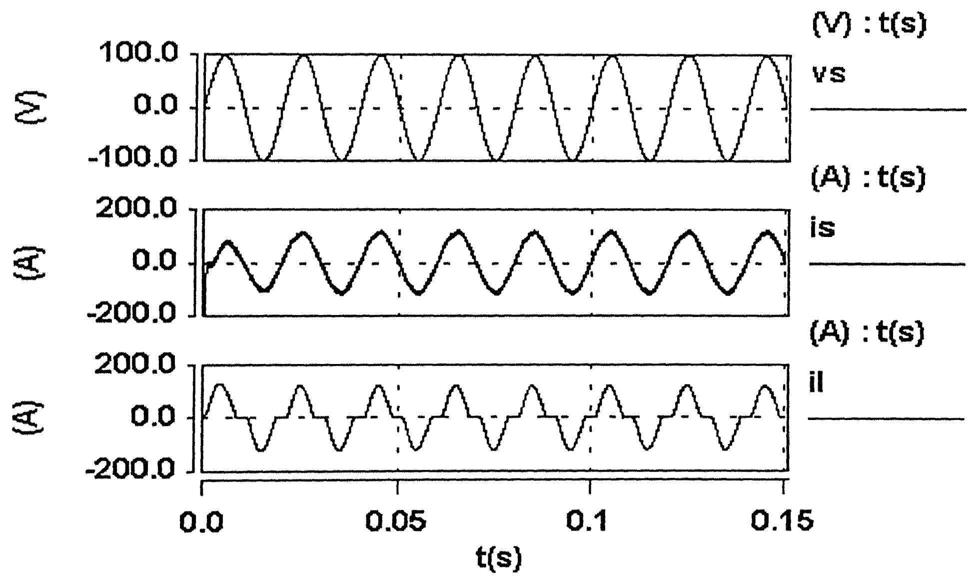

Fig. 2.6 Supply voltage, current and load current

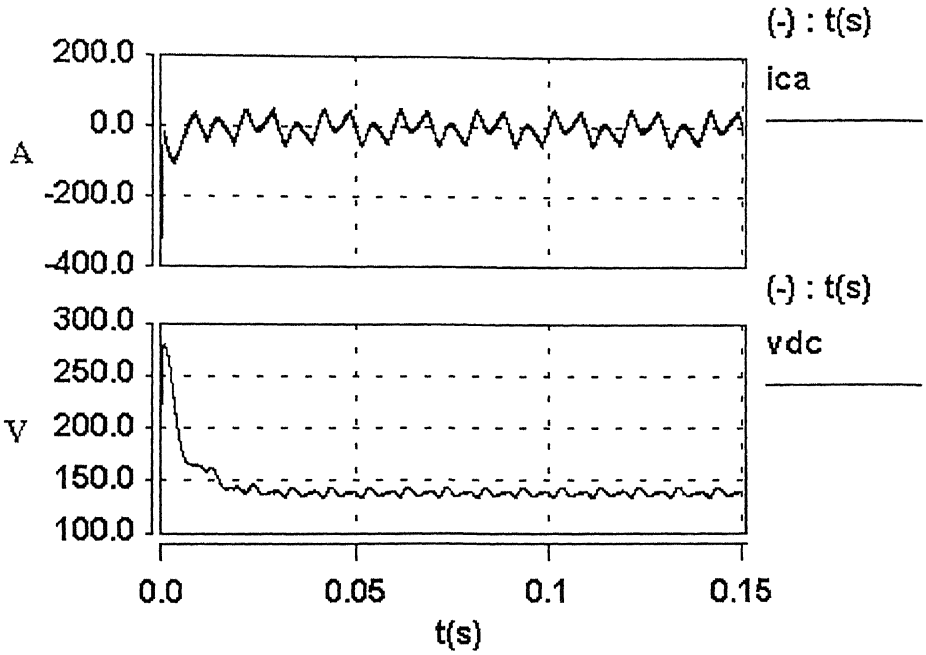

Fig. 2.7 Compensating current and dc link voltage

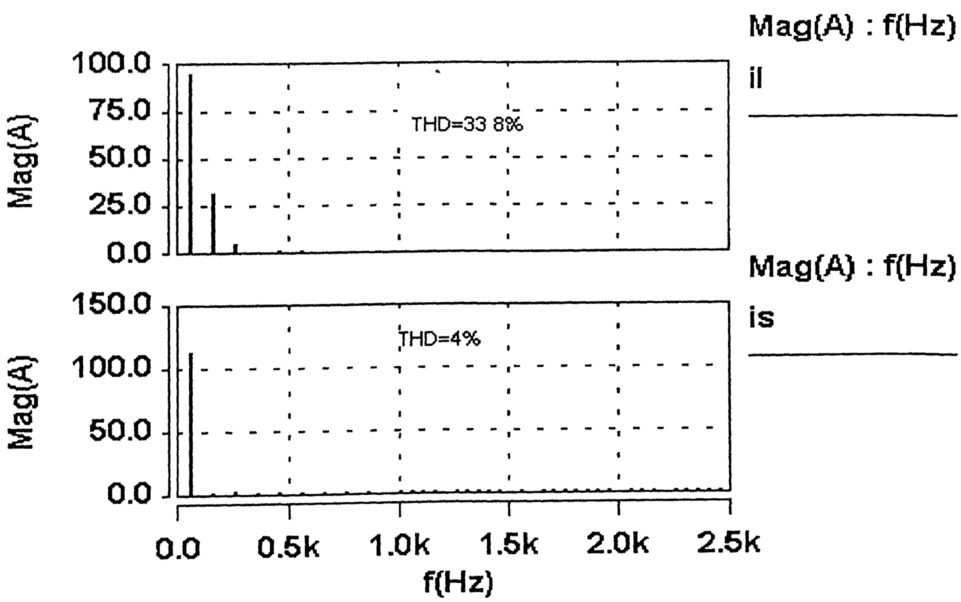

Fig. 2.8 Harmonic spectrum of load current and supply current

2.6.2 Compensation of inductive load

Figs. 2.9-2.10 show the performance characteristics of active power filter for compensating inductive load. The source voltage, v_s is single-phase 70.71V, 50Hz.

Specification of compensator

Capacitor	2000 μF
Synchronous Link Inductor	0.8 mH
Synchronous Link Resistor	0.5 Ω

Initially pure resistive load is connected. After 0.05 sec., an inductive load is switched on Fig. 2.9 shows that source voltage and source current are in phase, and dc link voltage during steady state condition 150V.

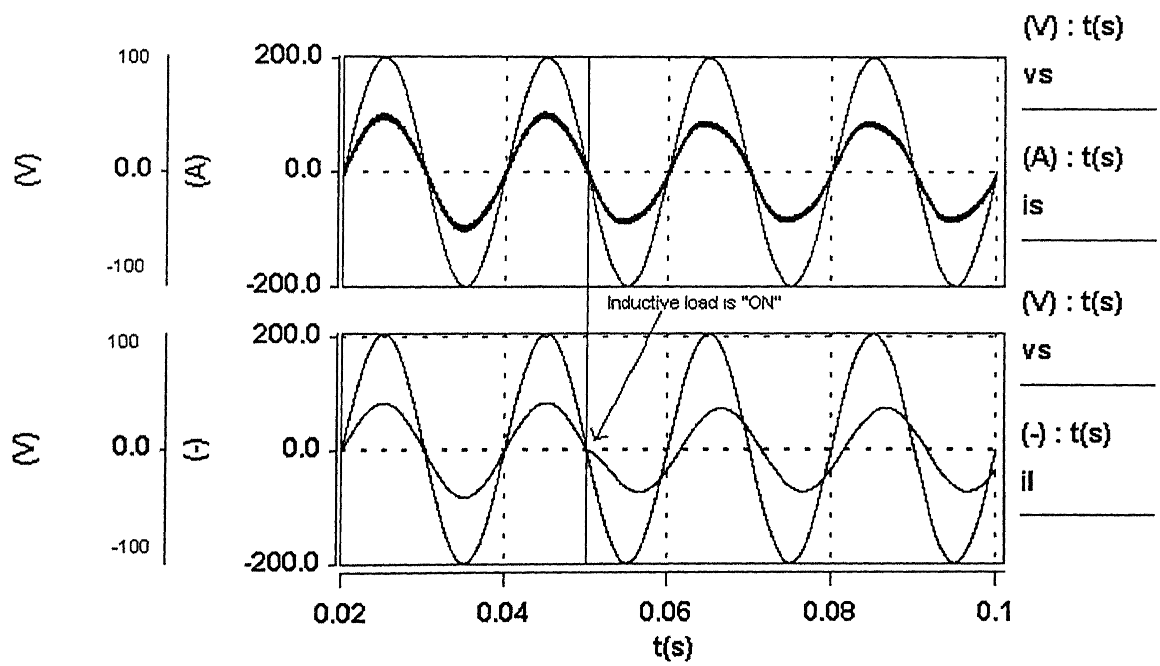

Fig. 2.9 Source voltage, current and load current

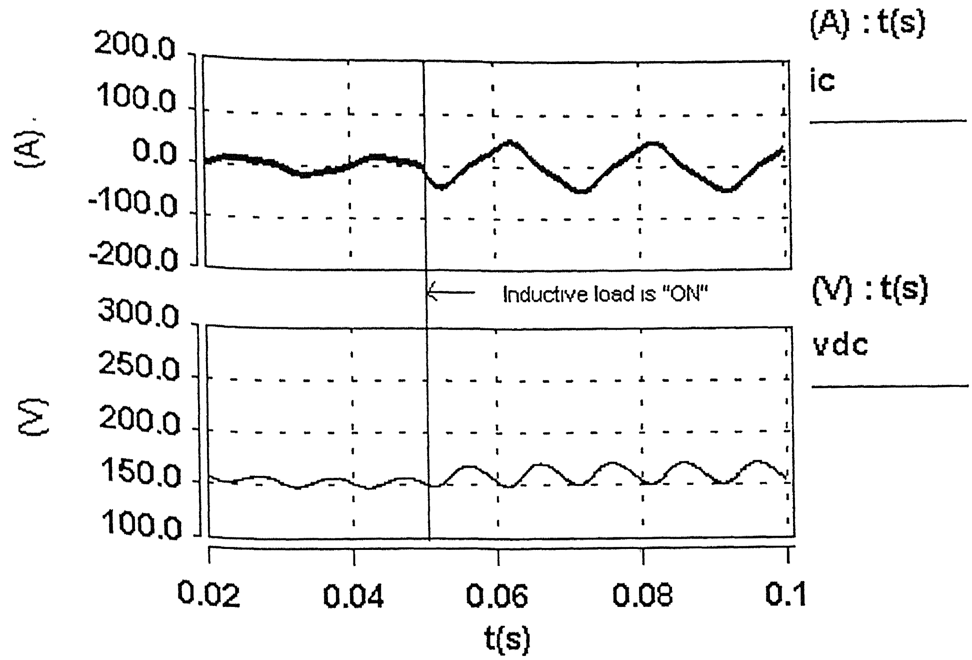

Fig. 2.10 Compensation current and dc link voltage

2.7 Conclusion

The simulated results of the single-phase active power filter using PI controller for the compensation of non-linear and an inductive loads have been presented. With the help of the APF, the harmonics in the load current is compensated to give a source current THD of 4%. The dc bus voltage regulation is found to be acceptable and during transient conditions the dc bus voltage oscillates before approaching a constant value.

CHAPTER 3

PERFORMANCE ANALYSIS OF ACTIVE POWER FILTER IN THREE-PHASE, THREE-WIRE SYSTEM

3.1 General

Most of ac power systems are designed for balanced operation. Compensation characteristics of the active power filter are modified to include load balancing aspect along with reactive power compensation and current harmonic elimination abilities. Section 3.2 presents the description of the system, which consists of ac source, APF and loads. Section 3.3 describes the control scheme for the three-phase system under steady. A mathematical model is required to examine the dynamic performance of the proposed APF. It becomes often desirable that even after having subjected to certain simplifying assumptions, the model so developed must represent the real time system. The mathematical model of the system used here consists of equations expressed in terms of operating variables of the system. Steady state and transient performance of active power filter is simulated for three-phase linear and non-linear loads with lagging power factor. The results demonstrate the harmonic filtering and reactive power compensation capabilities of the APF.

3.2 Description of the Three-phase, Three-wire System

The configuration of the three-phase, three-wire active power filter including load and supply system is shown in Fig. 3.1. This section presents a brief description of the active power filter and other important components required for its operation.

The shunt active power filter consists of a three-phase voltage source inverter with a dc bus storage capacitor The working of the system can be also be understood from the block diagram in the Fig. 3.2.

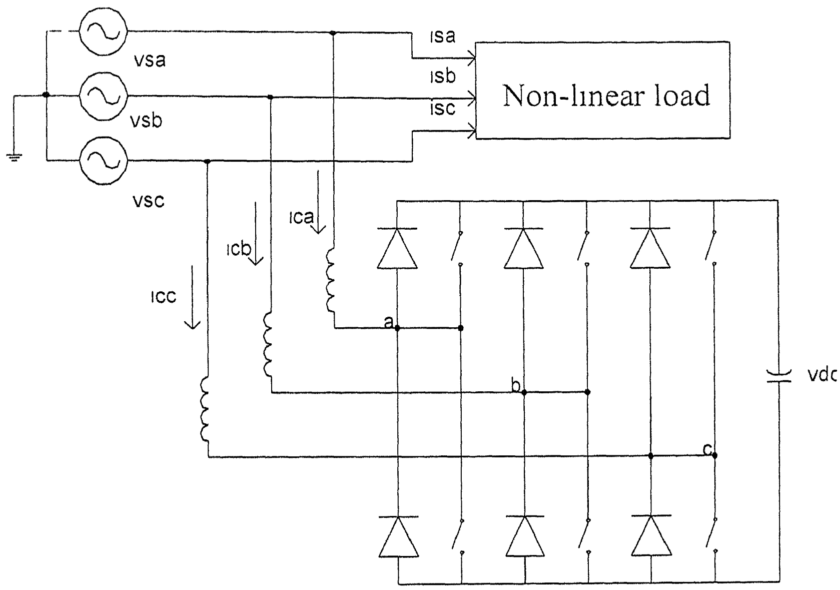

Fig.3.1 Basic circuit of the three-phase, three-wire shunt APF

The proposed system uses two control loops namely, dc link voltage control loop (outer loop) and current control loop (inner loop). Outer control loop is responsible for the generation of amplitude of reference supply current signal and inner loop is used for the realization of reference APF currents. With the help of instantaneously sensed supply voltages (v_{sa}, v_{sb}, v_{sc}) and limited output of outer control loop (I_{sm}*), instantaneous three-phase reference supply currents (i_{sa}*, i_{sb}*, i_{sc}*) are generated Three-phase instantaneous reference APF currents (i_{ca}*, i_{cb}*, i_{cc}*) are generated by using three-phase reference supply currents (i_{sa}*, i_{sb}*, i_{sc}*) and sensed load currents (i_{la}, i_{lb}, i_{lc}). The second loop, which is a current control loop, uses hysteresis current control to maintain actual APF currents (i_{ca}, i_{cb}, i_{cc}) in close proximity of reference APF currents (i_{ca}*, i_{cb}*, i_{cc}*).

Continuously varying balanced linear and non-linear loads are compensated by APF using the proportional integral controller.

3.3 Proportional-integral Controller

The PI controller, as shown in Fig 3 2, estimates the amplitude of reference supply current (I_{sm}*) To avoid oscillation in the steady state it is necessary to extract a steady voltage out of continuously varying voltage of dc bus capacitor This can be obtained by sensing the voltage of dc bus capacitor at every ripple period or by averaging dc bus capacitor voltage over ripple period

The comparator calculates the error between the reference voltage and the filtered dc bus capacitor voltage In response to the input error signal, the PI controller generates the output (I_{sm}*) In the event of any load disturbance, instantaneous voltage of the dc bus changes which is an input to the comparator. If load requirement increases, it is fulfilled by the active power filter instantaneously, which causes a dip in the in the APF capacitor voltage In response, output of the voltage error detector increases.

The output of the PI controller is fed to the limiter The limiter puts a limit on the reference supply current signal (I_{sm}*). Limiter is essential because on the sudden application or removal of loads, APF should not be allowed to carry currents beyond the rating of its switching devices. This may lead to blowing up of the inverter switching devices. The phase information for each phase is obtained by sensing the three-phase supply voltage (v_{sa}, v_{sb}, v_{sc}) instantaneously by using voltage sensors.

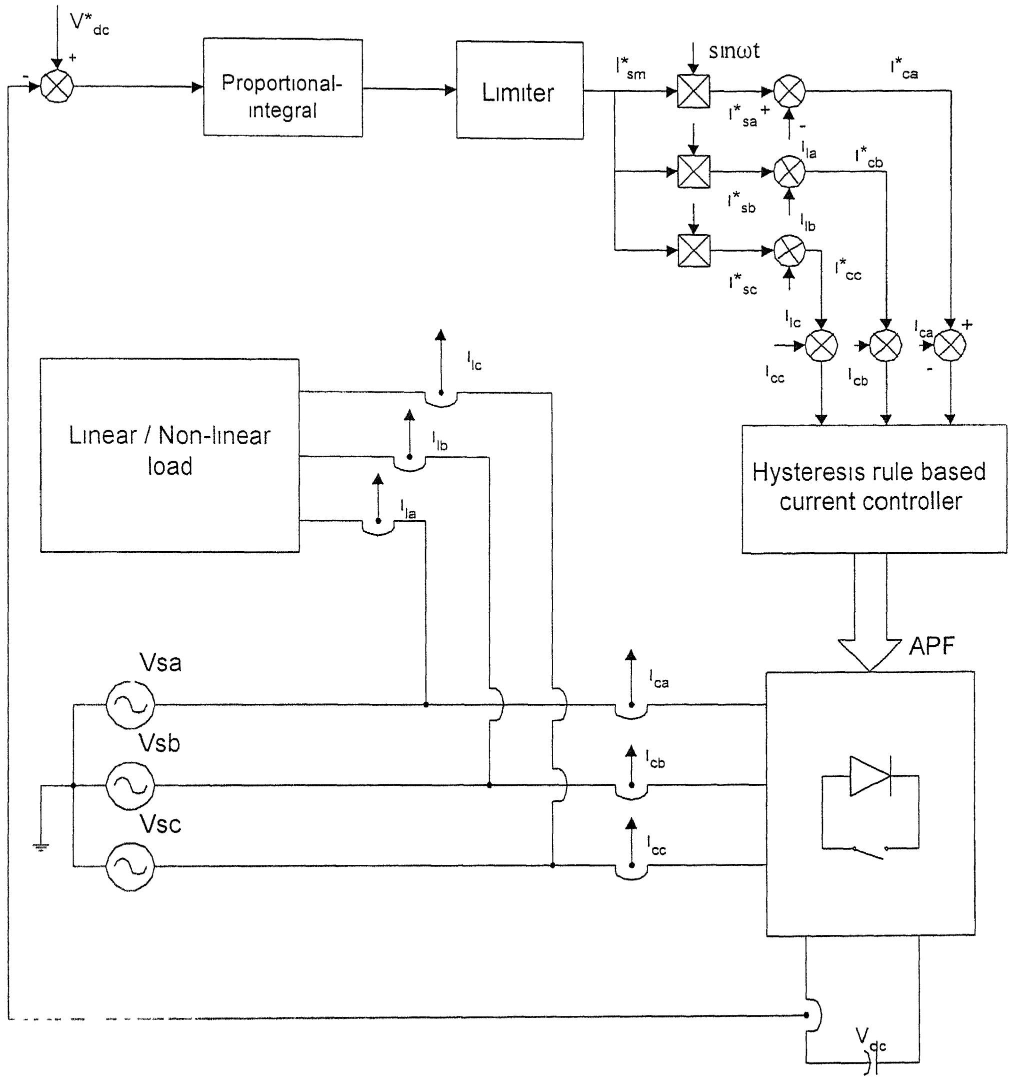

Fig 3.2 PI control scheme for three-phase, three-wire shunt APF

With the help of available magnitude (I_{sm}*) and phase information, three-phase instantaneous reference supply currents (i_{sa}*, i_{sb}*, i_{sc}*) are determined. With the help of instantaneous reference supply currents (i_{sa}*, i_{sb}*, i_{sc}*) and instantaneously sensed load currents (i_{la}, i_{lb}, i_{lc}), the three-phase reference APF currents (i_{ca}*, i_{cb}*, i_{cc}*) are estimated. Three current sensors are used to sense actual currents of the APF The active power filter

currents are controlled by using hysteresis current control. The output of current controller derives the gating signals for switching devices of the APF.

The operation of current controller has been explained here. On the basis of the defined hysteresis band h_b, two envelopes namely the upper and lower of phase reference APF current signals are formed, and the actual APF current signal is allowed to move within these two boundaries. If the APF current crosses the upper boundary of reference current signal, upper switching device of that phase leg is switched "on". This causes the dc link voltage to appear across inverter output terminal, opposing the flow of actual APF current. When APF current touches the lower boundary of the reference current signal, the lower switching device of that phase leg is turned "on". This results in a reverse polarity dc bus capacitor voltage to appear across inverter terminal, which increases the flow of APF current, forcing the current to stay within the defined boundary.

Similarly, all switching devices of three legs are switched "on" or "off" depending upon the status of actual three-phase APF currents relative to three-phase reference currents of the APF.

3.4 Mathematical Modelling of the System

The proposed APF system comprises three-phase, three-wire ac source, load, APF and its control schemes. In this section all components of the system are analyzed separately to develop a comprehensive model to simulate its behavior.

3.4.1 Supply system

Under normal operating conditions, three-phase supply system is of sinusoidal and balanced nature. The input ac voltages v_{sa}, v_{sb}, and v_{sc} are sensed with the help of three voltage sensors and given by:

$v_{sa}=V_{sm}\sin(\omega t)$

$v_{sb}=V_{sm}\sin(\omega t-120^{\circ})$

$v_{sc}=V_{sm}\sin(\omega t-240^{\circ})$

where V_{sm} is amplitude of source voltage and ω is the frequency in electrical radian/sec. The sensed voltages are used to derive the unit current templates in phase with ac source voltages as follows:

$u_{sa}=v_{sa}/V_{sm}$;

$u_{sb}=v_{sb}/V_{sm}$;

$u_{sc}=v_{sc}/V_{sm}$;

where V_{sm} is computed as.

$V_{sm}=\sqrt{\{2(v_{sa}^2+v_{sb}^2+v_{sc}^2)/3\}}$

3.4.2 Proportional integral controller

A simple PI control for dc bus capacitor voltage of APF is used for the closed loop control. The dc bus voltage is filtered and is compared with its reference value. The resulting voltage error at the nth sampling instant is expressed as:

$V_{e(n)}\ \ V_{dc}^{*}-V_{dca(n)}$

The output of PI controller $V_{o(n)}$ at the nth sampling instant is expressed as:

$V_{o(n)}-V_{o(n-1)}+K_p(V_{e(n)}-V_{e(n-1)})+K_iV_{e(n)}$

where K_p and K_i are respectively proportional and integral gain constants of voltage controller. The output $V_{o(n)}$ of voltage controller is taken as amplitude of source current (I_{sm}^{*}) after limiting it to a safe value.

3.4.3 Reference supply current generation

Using the above generated unit current templates and amplitude of reference supply current signal, instantaneous three-phase reference supply currents are computed as:

$i_{sa}^* = I_{sm}^* u_{sa}$, $i_{sb}^* = I_{sm}^* u_{sb}$; $i_{sc}^* = I_{sm}^* u_{sc}$

3.4.4 Reference active power filter current estimation

The three-phase reference APF currents are estimated with three-phase reference source instantaneous currents and sensed three-phase load current as follows·

$i_{ca}^* = i_{sa}^* - i_{la}$ $i_{cb}^* = i_{sb}^* - i_{lb}$ $i_{cc}^* = i_{sb}^* - i_{lc}$

3.4.5 Current controller

Hysteresis current control is used for fast control of APF currents. The current controller for three-phase APF currents generates the switching pattern to the APF devices Switching logics are :

Table no. 1

Instantaneous Current status	Phase	Upper switch	Lower switch
$i_{ca} < (i_{ca}^* - h_b)$	A	OFF	ON
$i_{ca} > (i_{ca}^* + h_b)$	A	ON	OFF
$i_{cb} < (i_{cb}^* - h_b)$	B	OFF	ON
$i_{cb} > (i_{cb}^* + h_b)$	B	ON	OFF
$i_{cc} < (i_{cc}^* - h_b)$	C	OFF	ON
$i_{cc} > (i_{cc}^* + h_b)$	C	ON	OFF

In the above table, h_b is the hysteresis band.

3.5 Simulation

This section presents the performance simulation of system shown in Fig. 3.1. The set of first order differential equations along with other expressions defined the dynamic model of APF system. All the simulation has been done by the SABER software and harmonic analysis of load current and source current has been done by SABER scope. Source voltage is three-phase balanced with constant amplitude and frequency. Loads are non-linear and inductive, for steady state simulation. For Dynamic performance evaluation, the loads are changed during the simulation.

Specification of three-phase APF

Supply voltage	35.35 V
Frequency	50 Hz
Link inductor	4 mH
Link resistor	0.8 Ω
Capacitor	6000 μF

3.6 Results and Discussion

In this section, the reactive power compensation and harmonic current elimination capabilities of APF are demonstrated by the results obtained from SABER simulation of the system.

3.6.1 Compensation of non-linear load

Active power filter is used for harmonic elimination from non-linear loads. For this purpose a three-phase uncontrolled diode bridge rectifier with resistive-capacitive loading is taken as the load. This type of load behaves as a non-linear balanced load. Peak amplitude of supply voltage is 50V, and frequency is 50Hz. In Fig. 3.3, balanced three-

phase non-linear load currents are shown up to 0.15sec., and load currents have harmonic distortion. Fig. 3.4 shows balanced three-phase voltage source and source currents, which are fully sinusoidal with unity power factor. The THD of the source current is 3.9%. Harmonic spectrum is shown in Fig. 3.6.

Fig. 3.5 shows compensating current which is also balanced. The dc link voltage is more than 150V, which is three times of peak amplitude of source voltage.

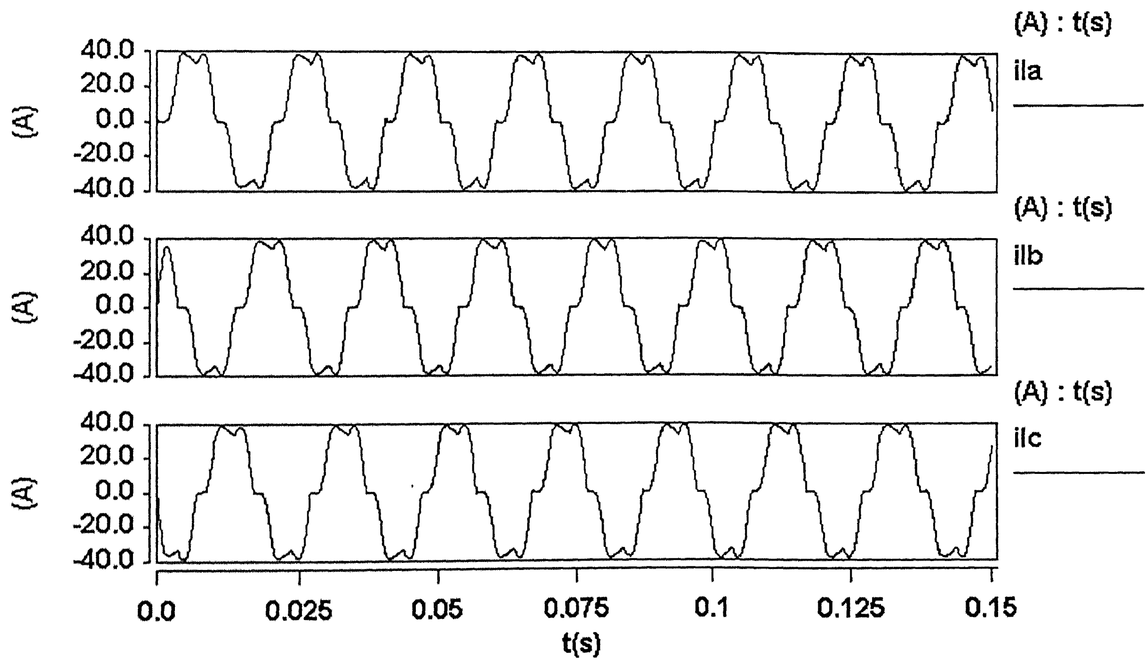

Fig. 3.3 Three-phase non-linear load currents

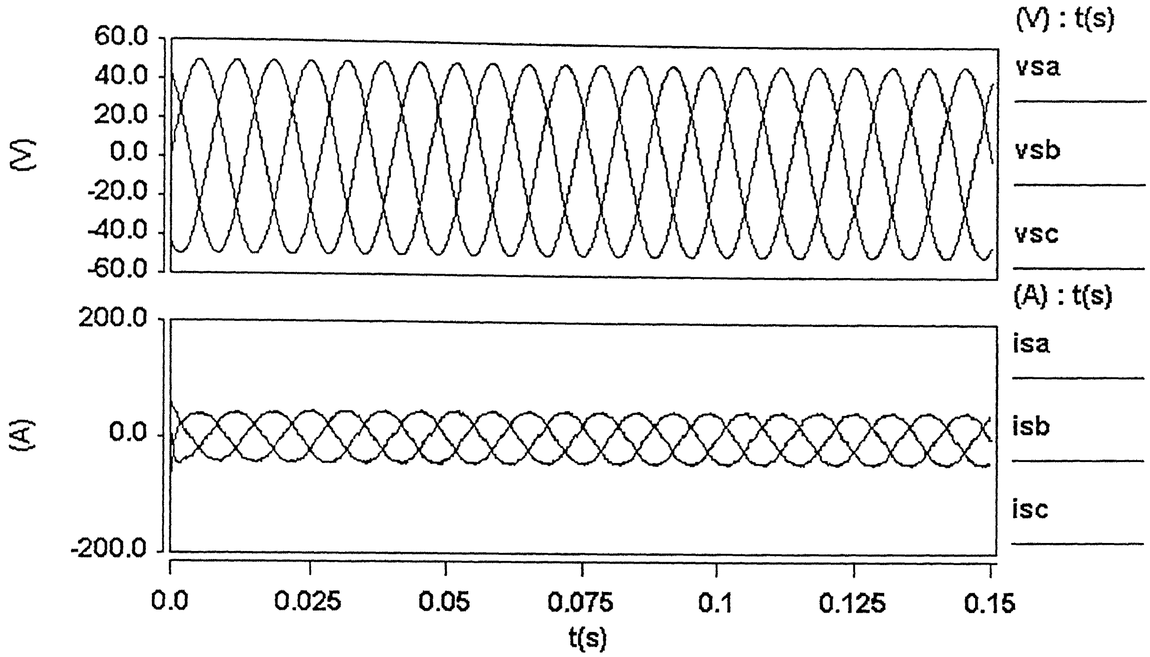

Fig. 3.4 Source voltage and current

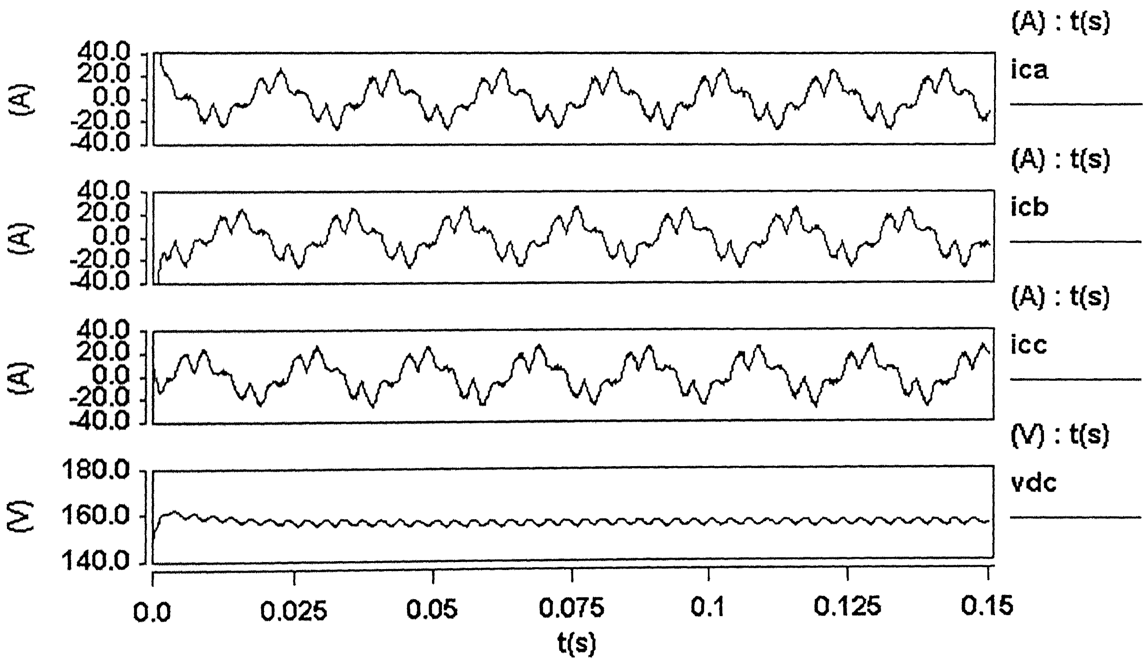

Fig. 3.5 Compensating currents and dc link voltage

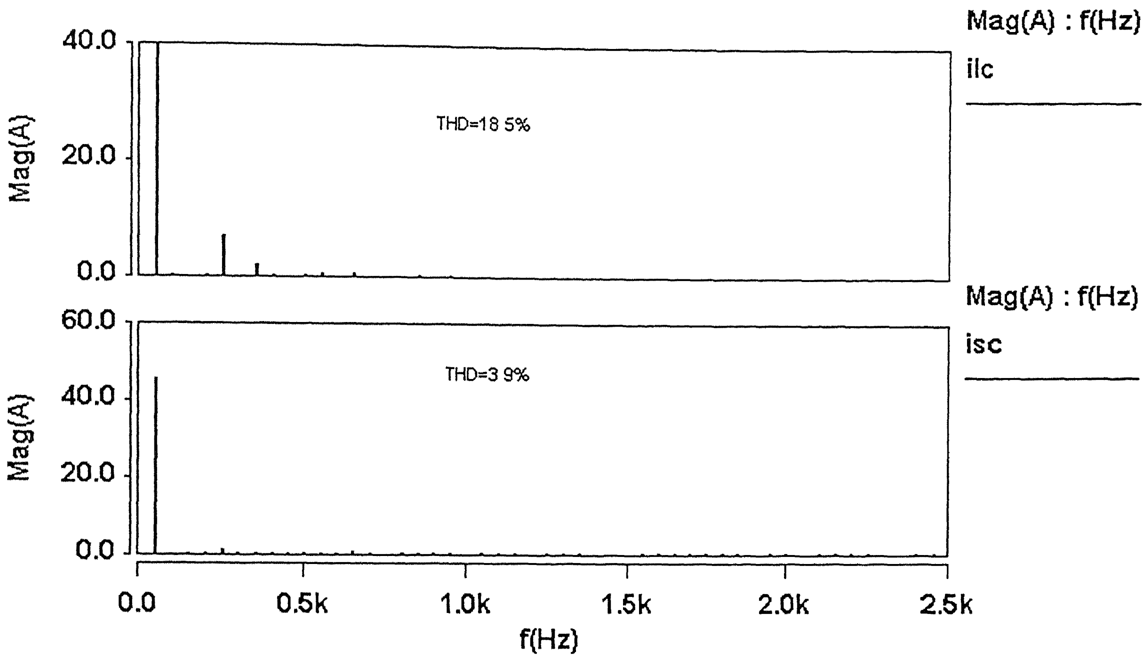

Fig. 3.6 Harmonic spectrum of load and source currents

3.6.2 Compensation of inductive loads

Figs. 3.7-3.8 present the steady state and dynamic performance of the active power filter. Three-phase balanced inductive loads are connected and currents have 30° phase lag from the phase voltage, and this is shown in Fig. 3.7. After 0.1sec., the inductive loads are switched off, leaving only the resistive load connected. The switching of load from inductive to resistive gives dynamic performance of the compensator. From Fig. 3.7 there is no effect on the source current but compensating currents are approaching to zero value, which is shown in Fig. 3.8. The dc link voltage is shown in Fig. 3.8 during this transient.

3.7 Conclusion

A three-phase three-wire APF suitable for compensation of non-linear and lagging power factor loads has been presented. The APF compensates the harmonics in load current resulting in a source THD of 3.9% which is within the specified IEEE-519 standard. The APF also provides VAR compensation, which makes source current power factor unity.

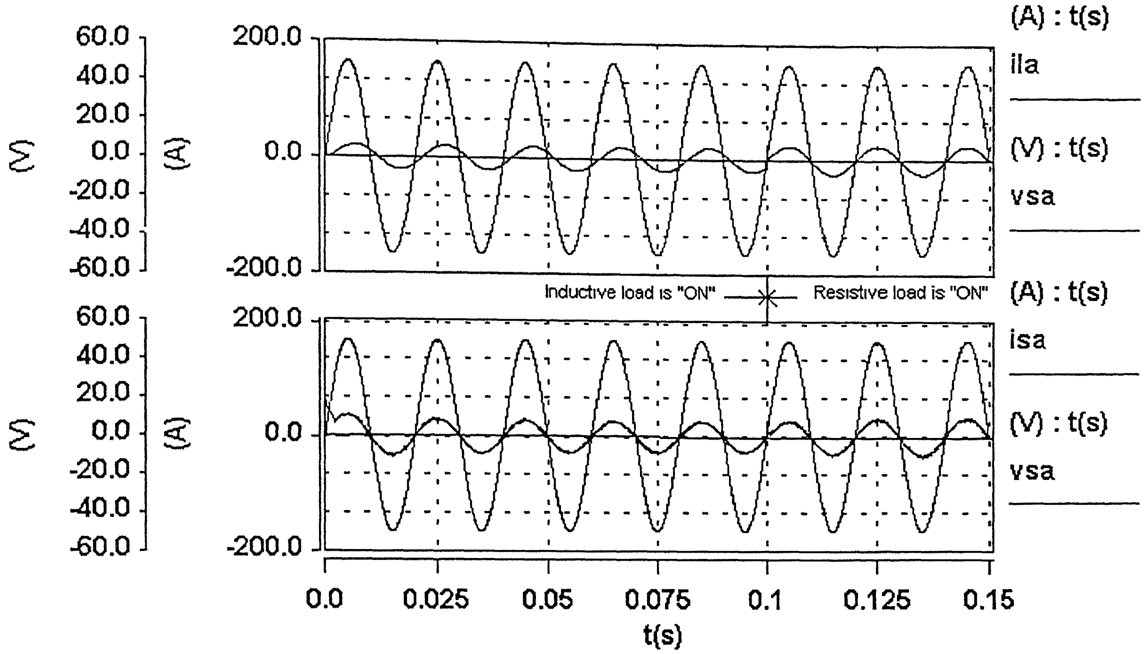

Fig. 3.7 Inductive load current and compensated source current with supply voltage

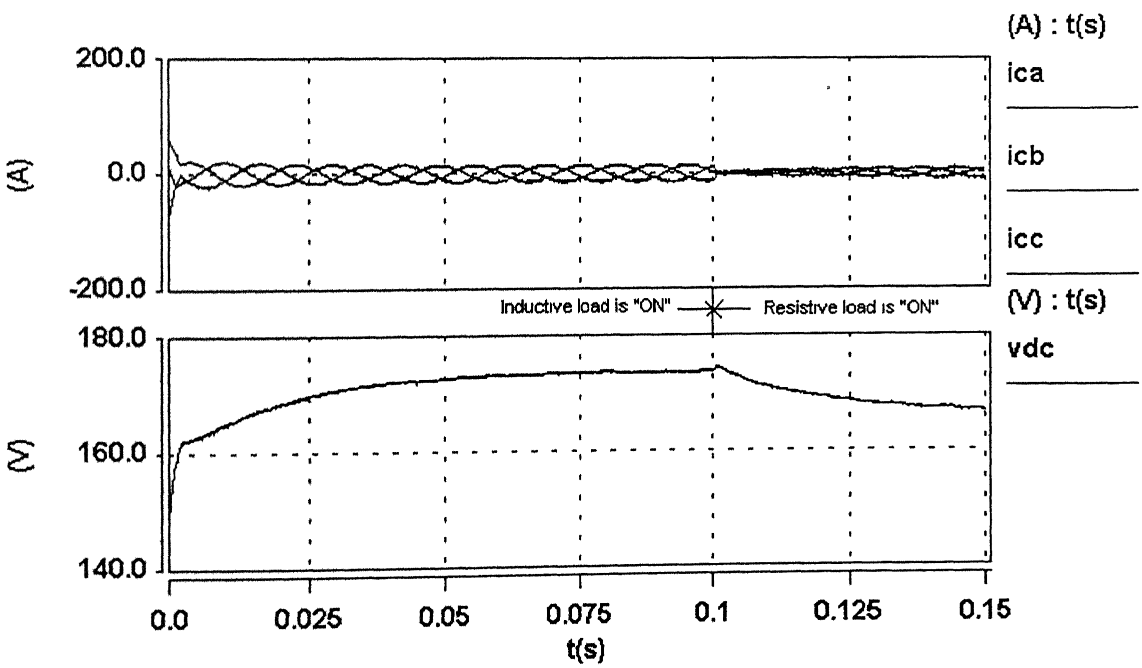

Fig. 3.8 Compensating currents and dc link voltage

CHAPTER 4

PERFORMANCE ANALYSIS OF ACTIVE POWER FILTER IN THREE-PHASE, FOUR-WIRE SYSTEM

4.1 General

In the previous chapter an extensive and detailed study of active power filter in three-phase, three-wire system is carried out. Such filter is capable to deal with balanced non-linear and reactive loads. The compensation of balanced and unbalanced compensated load in three-phase four-wire system is also important, because unbalanced and uncompensated loads can give rise to excessive neutral current and deteriorate the quality power. Two configurations of VSI based active power filter using either three single-phase voltage source inverters and four-leg voltage source inverter are used as active power filter in three-phase, four-wire distribution system. Single-phase unequal lagging power factor linear loads may result in large current in neutral wire of the three-phase, four-wire system. Such loads are considered for reactive power compensation, load balancing and neutral current compensation. Single-phase equal non-linear loads can also cause significant neutral currents, because of third harmonic and odd multiples of 3rd (i.e. 9th, 15th etc.) which are co-phasal and do not cancel each other in the neutral. A set of three single-phase equal non-linear loads are considered to demonstrate reactive power compensation, harmonic elimination and neutral current compensation (mainly consist of zero sequence component of load current). Controller is expected to control the active power filter to perform the reactive power compensation, neutral current compensation and current harmonic elimination of such loads.

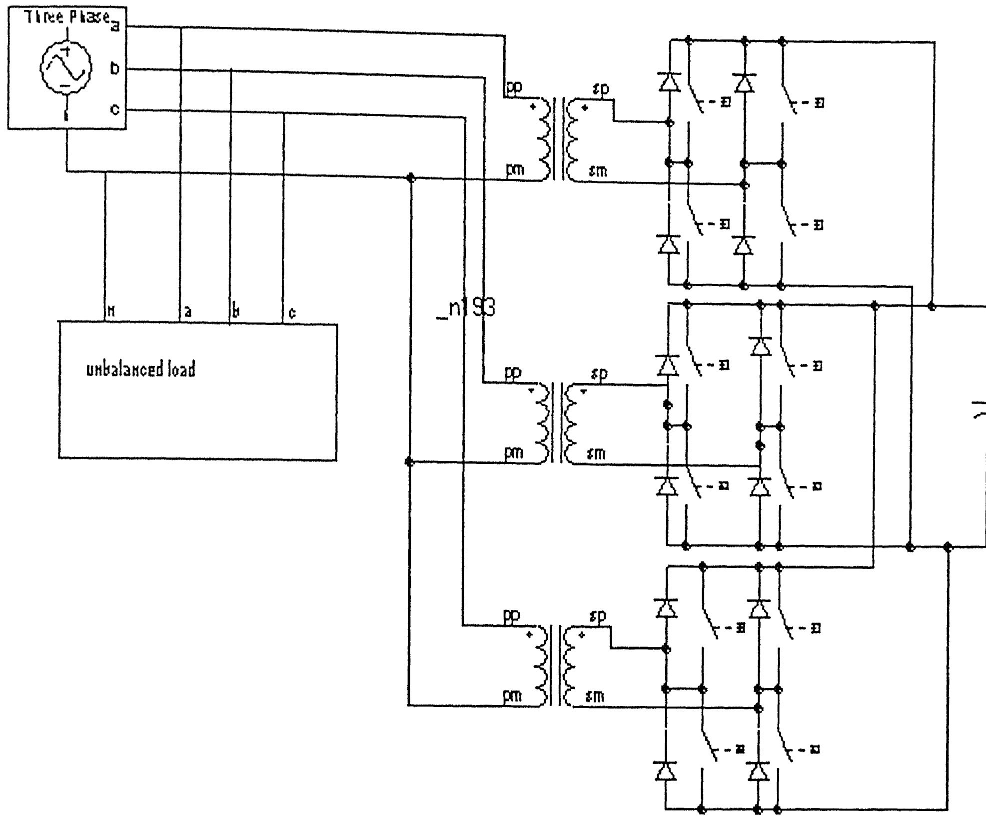

Fig. 4.1 Basic circuit of the three-phase, four-wire shunt APF

4.2 Problems Associated with Neutral Current

In three-phase, four-wire supply system, neutral current is the sum of three line-to-neutral currents. With balanced three-phase sinusoidal currents, which consist of sine waves spaced 120 electrical degrees apart, the sum at any instant of time is zero, and so there is no neutral current. However, in practice, unbalance in phase currents may occur due to various practical limitations. The generation of neutral current into balanced supply can be (i) due to load unbalance (ii) due to presence of non-linear loads.

In most three-phase power systems supplying single-phase loads, there will be some phase current unbalance resulting in some neutral current.

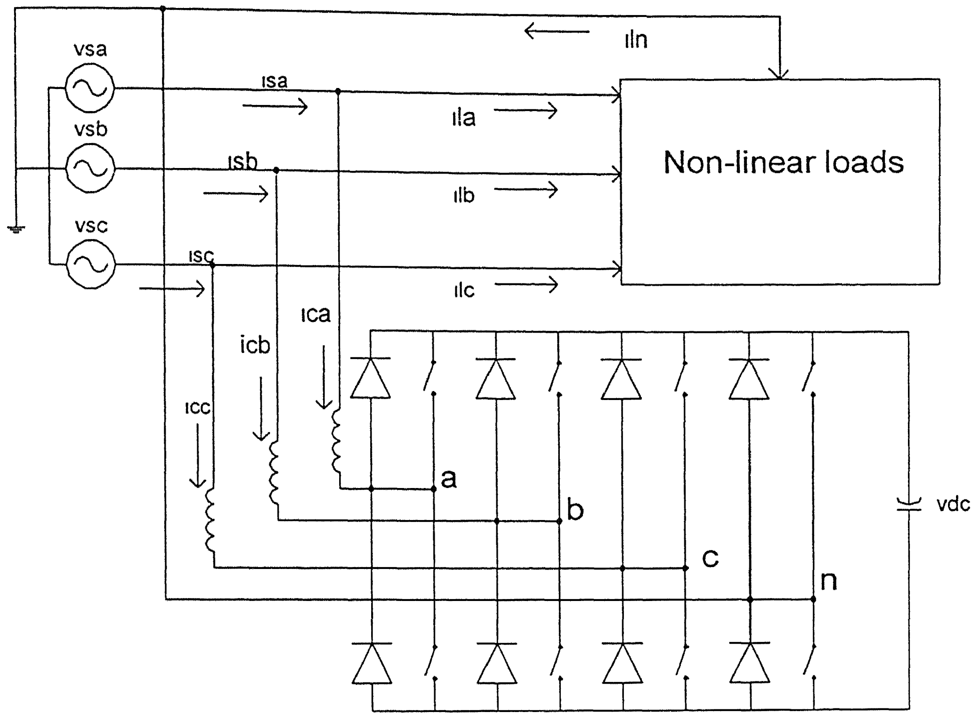

Fig. 4.2 Basic circuit of the three-phase, four-wire shunt APF using four-legs

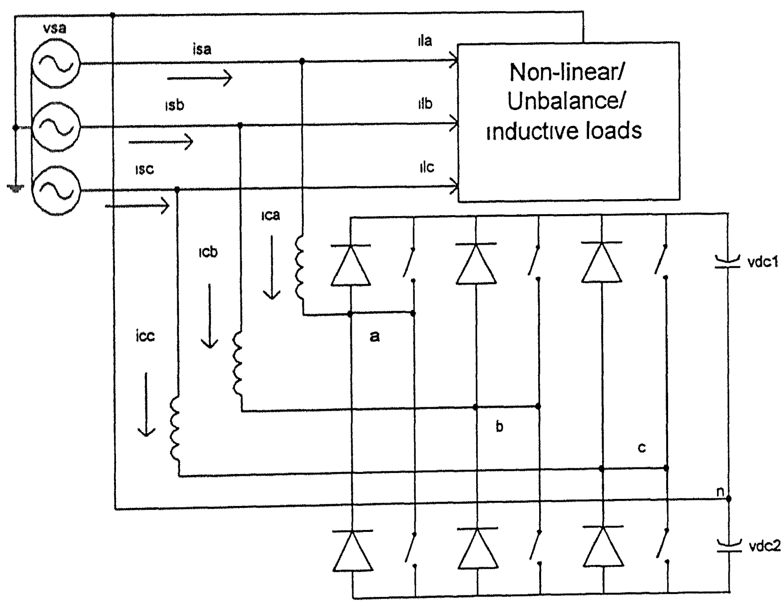

Fig. 4.3 Basic circuit of the three-phase, four-wire shunt APF using split capacitor

Small neutral current resulting from slightly unbalanced loads does not cause problems for typical building power distribution systems. However, significantly unbalanced linear loads cause the flow of current into neutral wire, which may larger than what neutral wire is rated for.

There are conditions, where even perfectly balanced single-phase loads can result in significant neutral currents. Non-linear loads have phase currents which are not sinusoidal. The sum of balanced, nonsinusoidal, three-phase current is not necessarily zero. In three-phase circuits, the triplen harmonics neutral currents (third, ninth, etc.) add instead of cancel. The triplen harmonic currents are in phase with each other, therefore, add in the neutral circuit.

The situation becomes worse when three-phase unbalanced non-linear loads are existing in three-phase, four-wire supply system. Neutral current because of load unbalance and triplen harmonics adds up and rises to excessively to high values.

Potential problems directly related to excessive harmonic currents in the neutral conductor are:

(i) Wiring failure due to improper sizing of the neutral conductor.

(ii) Overheating of the transformer due to harmonic currents, insulation damage and failure.

(iii) Excessive neutral to ground voltage due to voltage drop caused by the neutral current.

This common mode potential can result in the malfunction of sensitive electronic components. In view of above highlighted problems, it becomes imperative to reduce neutral current below the acceptable levels.

4.3 Description of Three-phase, Four-wire System

This section discusses overall system structure including loads Figs. 4.2 and 4.3 show the schematic diagrams of active power filters connected in parallel to the ac mains and load Fig. 4 2 shows the circuit of an active power filter, comprising power electronics switches based voltage source inverter Its working principle is similar to three-phase voltage source inverter with three-phase legs controlling current in each phase However, a fourth leg is added to control the current in neutral wire, thereby introducing current in neutral wire in phase opposition to load neutral current

Selection of three single-phase voltage inverters as an APF as shown in Fig 4.1, is made because it facilitates independent control of all the three-phases, leads to less voltage stresses on the solid state devices of active power filter, and provides isolation from the main circuit and a return path to neutral. Four-leg voltage source inverter configuration (Fig. 4.2) as active power filter offers use of less complex and more reliable control circuitry, but more voltage stresses on the solid state devices as compared to three single-phase VSIs. It also requires larger dc bus capacitor voltage since solid state devices switch only half of actual dc bus capacitor voltage therefore more losses in the active power filter can be predicted. However, in low voltage distribution systems, this may be preferred because of its above stated advantages.

Fig. 4.4 shows the schematic control block diagram for a four-leg VSI APF. With three single-phase VSIs as an APF only i_{nc}^* is not generated. As explained in chapters 2 and 3, two control loops are employed. Outer loop determines the amplitude of reference supply current signal (I_{sm}^*). The instantaneous reference supply current (i_{sa}^*, i_{sb}^*, i_{sc}^*) signals are estimated by using there-phase instantaneous sensed phase voltages (v_{sa}, v_{sb}, v_{sc}) and

limited output of the controller (I_{sm}^*) Instantaneous APF reference currents (i_{ca}^*, i_{cb}^*, i_{cc}^*) are generated by using instantaneous supply reference signals (i_{sa}^*, i_{sb}^*, i_{sc}^*) and sensed three-phase loads currents (i_{la}, i_{lb}, i_{lc}). Such generated three-phase current signals work as reference to the three single-phase VSI bridges. The reference APF neutral current (i_{nc}^*) of four pole VSI bridge is computed by using the sensed load currents A hysteresis based current control is employed over reference and sensed APF currents to achieve fast response. Three, two, or one single-phase linear / non-linear loads can be compensated by using APF circuits in three-phase, four-wire system

4.4 Proportional Integral Controller

Fig. 4.4 shows the basic overall control scheme with a PI controller. The amplitude of reference supply current (I_{sm}^*) is generated by employing PI voltage control on dc bus capacitor voltage of active power filter. The dc bus voltage is sensed using a voltage sensor. The averaged voltage of the dc bus capacitor of APF and its preset reference value are fed to an error detector. The output of the error detector is the input to the PI controller. If dc bus capacitor voltage of APF dips, controller increases its output to restore the dc capacitor voltage and if the error is negative then output of controller reduces so that capacitor discharges some of its energy in load and returns back to the reference value. In this manner, the voltage on the dc bus of an active power filter is regulated. The limited output of controller becomes the amplitude of reference supply currents (I_{sm}^*).

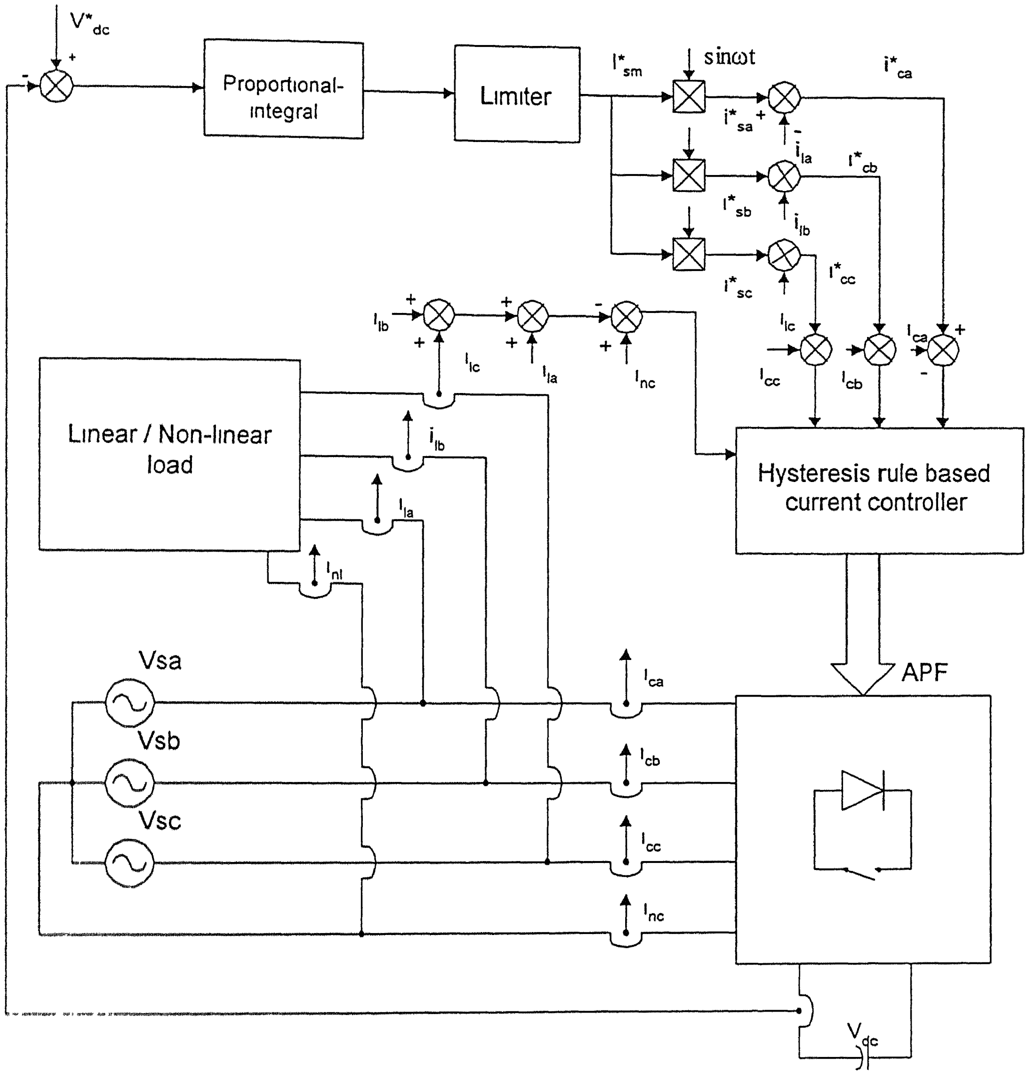

Fig. 4.4 Proportional-integral control scheme for three-phase, four-wire APF

4.5 Mathematical Modelling of the System

Mathematical model of proposed APFs are developed including ac supply system and load. Basic equations governing the system dynamics are presented in this section to give insight into APF working principle.

4.5.1 Supply system

Under normal operating conditions, supply voltages can be modulated as balanced sinusoidal supply voltages and may be expressed as:

$v_{sa}=V_{sm}\sin(\omega t)$

$v_{sb}=V_{sm}\sin(\omega t-120^\circ)$

$v_{sc}=V_{sm}\sin(\omega t-240^\circ)$

where V_{sm} is the peak value of source voltage and ω is its frequency in electrical radian / second.

u_{sa}, u_{sb} and u_{sc} the unit current vectors, are derived using instantaneously sensed three-phase supply voltage as:

$u_{sa}=v_{sa}/V_{sm}$,

$u_{sb}=v_{sb}/V_{sm}$;

$u_{sc}=v_{sc}/V_{sm}$;

V_{sm}, the amplitude of the supply voltage, is derived as:

$V_{sm}=\sqrt{\{2(v_{sa}^2+v_{sb}^2+v_{sc}^2)/3\}}$

4.5.2 Proportional-integral controller

Modeling of PI controller is presented in this section. Amplitude of reference supply current (I_{sm}^*) is estimated using PI control over the averaged dc bus capacitor voltage of APF. Average dc bus voltage ($V_{dca(n)}$) is compared with its reference value (V_{dc}^*) The resulting voltage error $V_{e(n)}$ at nth sampling instant is expressed as:

$V_{e(n)}=V_{dc}^*-V_{dca(n)}$

Output of PI controller can be expresses as:

$V_{o(n)}=V_{o(n-1)}+K_p(V_{e(n)}-V_{e(n-1)})+K_I V_{e(n)}$

where K_p and K_I are proportional and integral gain constants of voltage controller. Limited value of output $V_{o(n)}$ is taken as amplitude of source current (I_{sm}^*).

4.5.3 Reference supply current generation

Three-phase balanced reference supply currents are estimated using the output of the controller (I_{sm}^*) and derived unit current vectors as follows

$i_{sa}^* = I_{sm}^* u_{sa}$, $i_{sb}^* = I_{sm}^* u_{sb}$, $i_{sc}^* = I_{sm}^* u_{sb}$;

4.5.4 Reference active power filter current estimation

Instantaneous reference currents of active power filter are estimated from reference supply current and sensed load currents as:

$i_{ca}^* = i_{sa}^* - i_{la}$

$i_{cb}^* = i_{sb}^* - i_{lb}$

$i_{cc}^* = i_{sc}^* - i_{lc}$

$i_{nc}^* = -(i_{la} + i_{lb} + i_{lc})$

4.5.5 Current controller

The APF consists of power electronics switches based four-leg voltage source inverter using dc bus capacitor as an energy storage element. The switching logic can be formulated on the basic of status of the actual current and the reference current of the active power filter. For example:

- If $i_{ca} < (i_{ca}^* - h_b)$ upper switch is OFF and lower switch is ON in phase "a" leg
- If $i_{ca} > (i_{ca}^* + h_b)$ upper switch is ON and lower switch is OFF in phase "a" leg

where h_b is the width of hysteresis band.

4.6 Simulation

This section presents simulation and performance of system shown in Fig. 4.2 and Fig. 4.3. Control scheme given in Fig. 4.4 is med and all the simulation have been done with the help of SABER. Two topologies of three-phase, four-wire active power filters have been considered here. One is a four-leg VSI based APF and another is a VSI with a centre tap capacitor. Three types of loads have been simulated here. Initially, non-linear load is considered. Subsequently, balanced and unbalanced inductive loads have been.

Specification of fourth leg three-phase, four-wire active power filter

Supply voltage	35.53 V
Supply frequency	50 Hz
Peak amplitude of supply voltage	50 V
Link inductor	6 mH
Link resistor	0.6 Ω
Capacitor of dc link	6000 μF

Specification of split-capacitor three-phase, four-wire active power filter

Supply voltage	35.53 V
Supply frequency	50 Hz
Peak amplitude of supply voltage	50 V
Link inductor	4 mH
Link resistor	1 Ω
Capacitor of dc link	12000 μF

Three-phase four-wire four legs active power filter is simulated and waveforms are given in the Figs. 4.5-4.18. For split capacitor APF, the waveforms are given in the Fig. 4.19-4.30.

4.7 Results and Discussion

This section presents the simulation results and performance evaluation of both the active power filter circuits (four-leg and split capacitor of APFs configuration shown in Fig. 4.2 and 4.3 respectively), while the feeding balanced / unbalance / non-linear / inductive loads.

4.7.1 Compensation of non-linear load

A single-phase diode bridge rectifier feeding resistive-capacitive load is considered for non-linear loading of each phase. The capacitor at the output of uncontrolled diode bridge rectifier of every phase draws current of peaky nature and consists of mainly fundamental, third, fifth and seventh order harmonics. Load current is shown in Fig. 4.5. In Fig 4.6, source voltage and source current are shown which reveal balanced current and unity power factor. Fig. 4.8 shows harmonic spectrum of load and source currents and THD change from 22.36% to 3.86%. Compensator current is given in Fig. 4.7. Neutral current is flowing between the load neutral point and compensator neutral point but it is absent in the source neutral wire, and this is shown in the Fig. 4.9. The dc link voltage 160V and it is constant in the steady state.

4.7.2 Compensation of inductive load

Inductive balanced loads are considered here drawing current from voltage with phase lag of 60° as shown in Fig. 4.10. Fig. 4.11 shows the compensating currents. Neutral current is zero and the dc link voltage is constant at 170V as shown in Fig. 4.12.

4.7.3 Compensation of unbalance load current

A load current of one phase is "off" or the load is disconnected as shown in Fig. 4.13, and also the source currents are found fully balanced. Similarly, two phases of loads are disconnected as shown in Fig. 4.16. However, the source currents are fully balanced as given in the same figure. Figs. 4.14 and 4.17 show compensating currents and the dc link voltage variation is show in Fig. 4.15. Fig. 4.18 shows the dc link voltage, neutral currents of load and source when a single phase load is switched on.

4.7.4 Compensation of non-linear / inductive / unbalanced loads by 3-Φ, 4-wire split capacitor

Basic configuration of three-phase four-wire split capacitor is shown in the Fig. 4.3, and simulated wave forms are given in Figs. 4.19-4.30. Fig. 4.19 shows performance of the APF under steady state conditions, load current has harmonics. Load current THD 22% but by the controller it has been reduced to 4.6% in the source current as shown in Fig. 4.21. Source current is at unity power factor and three-phase voltage waveforms are given in the Fig. 4.20. Neutral current is flowing between load neutral point and compensator point but it is absent in the source side neutral wire. The VAR compensation capability is shown in the Fig. 4.24. The neutral current is not flowing in the load side and also in the source side as the loads are balanced in Fig. 4.26. The compensator current is given for inductive load compensation in Fig. 4.25. Loads are balanced till 0.05sec. but after 0.05sec., one line of load is switched "off" so loads are unbalanced, as shown in the Fig. 4.27. The source currents are shown in Fig. 4.28. After 0.1sec. again another line of load is switched "off". So there is only one line of load is connected with

source. But the source current is fully balanced and the neutral current is only flowing during transient period as shown in Fig. 4.30.

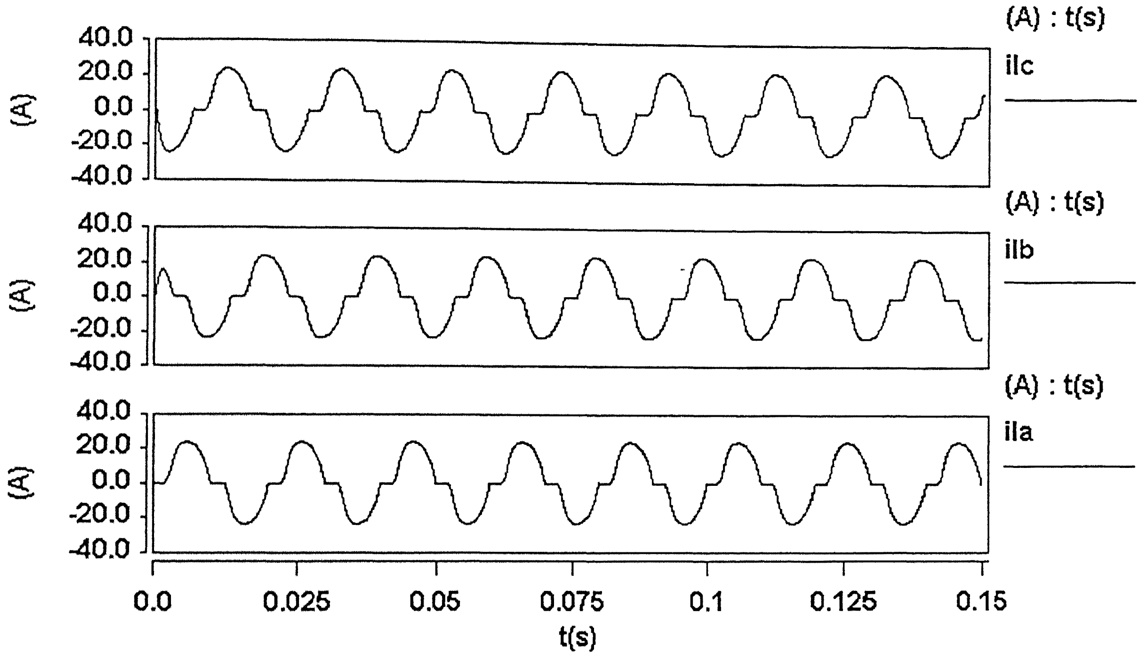

Fig. 4.5 Three-phase non-linear load currents

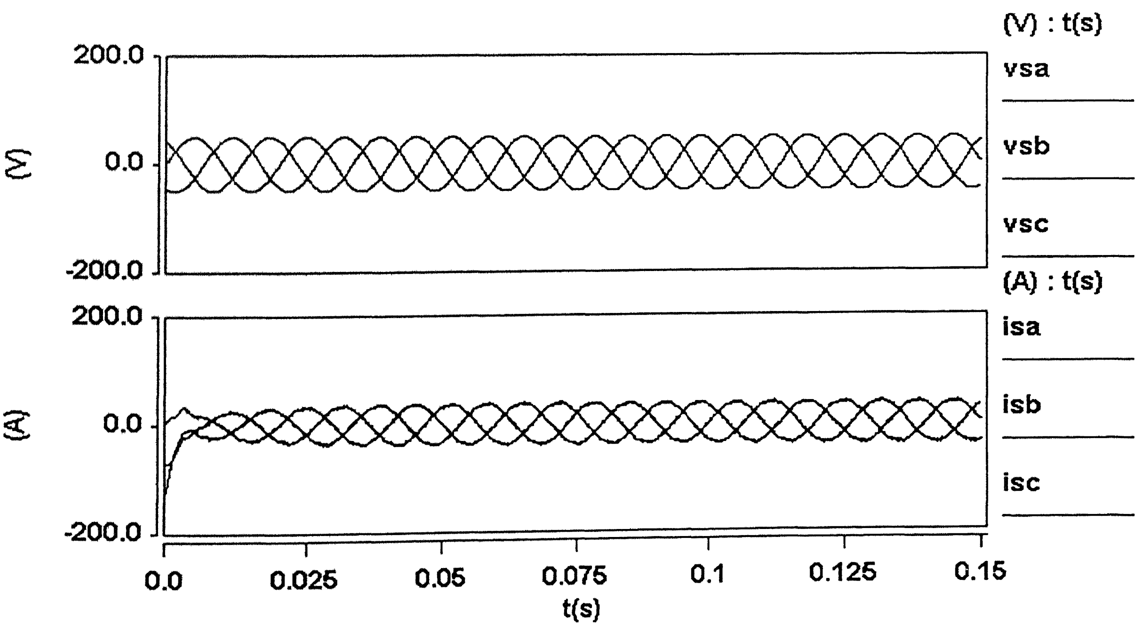

Fig. 4.6 Source voltage and fully balanced source current

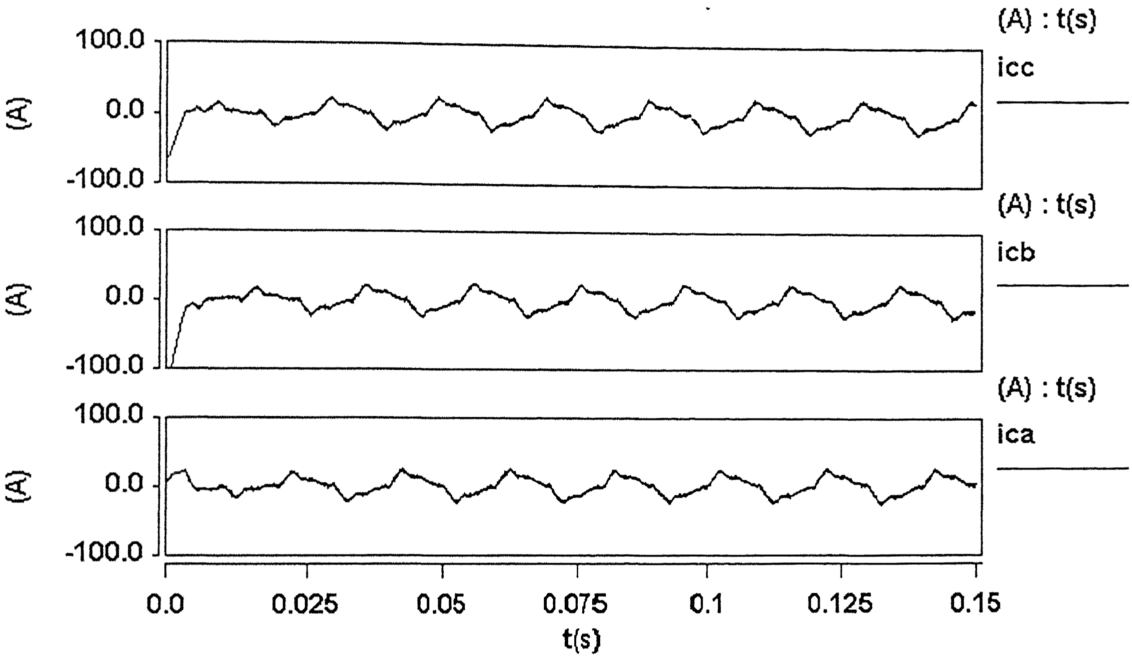

Fig. 4.7 Compensating current of three-phase system

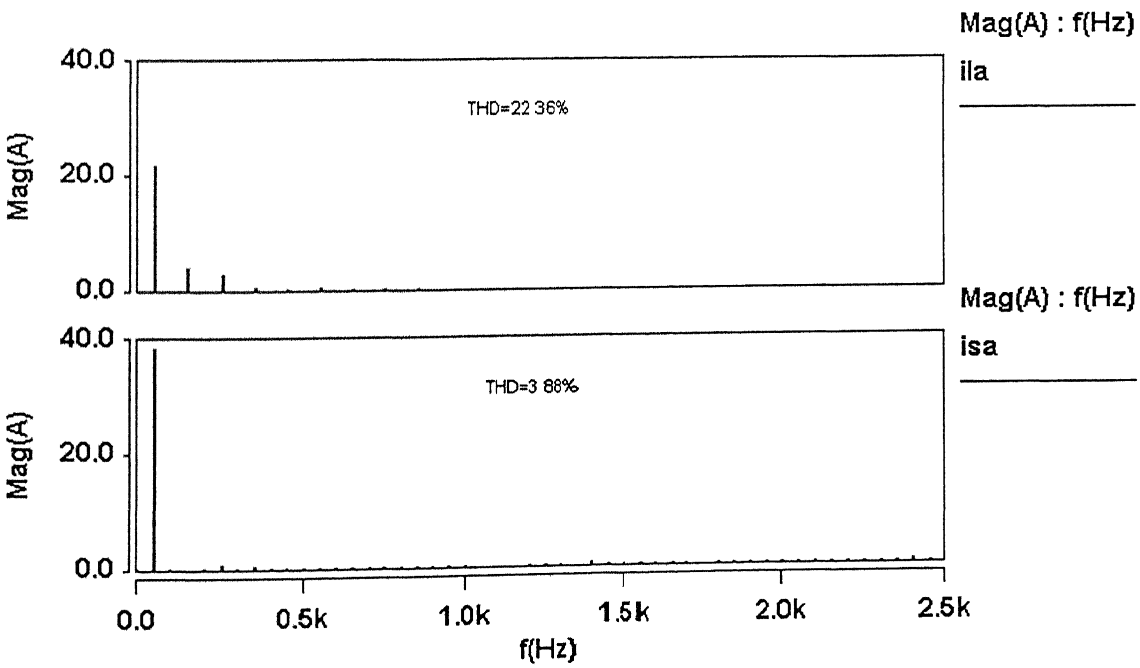

Fig. 4.8 Harmonic spectrum of load current and source current

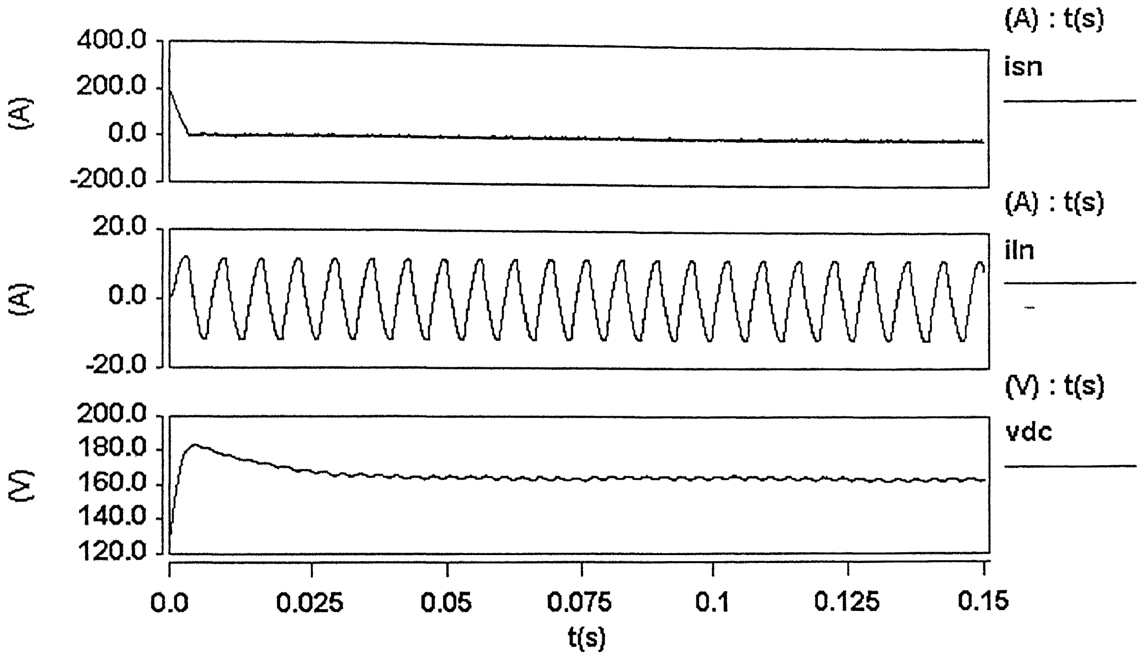

Fig. 4.9 Neutral currents in the source side and load side, dc link voltage

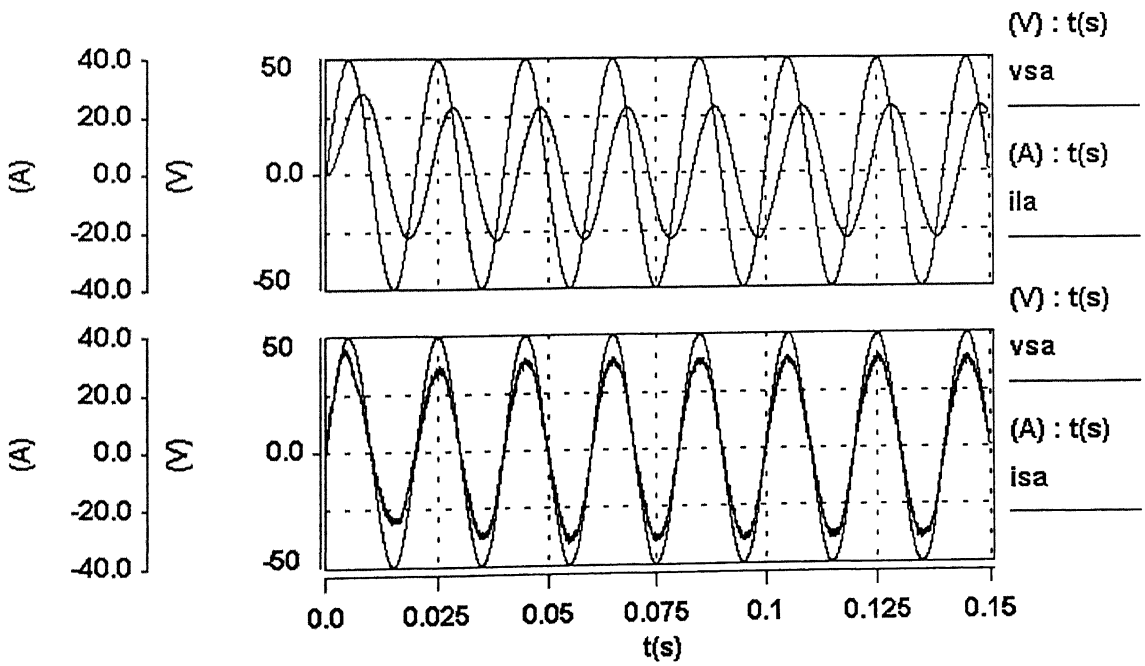

Fig. 4.10 Source voltage and current, inductive load current

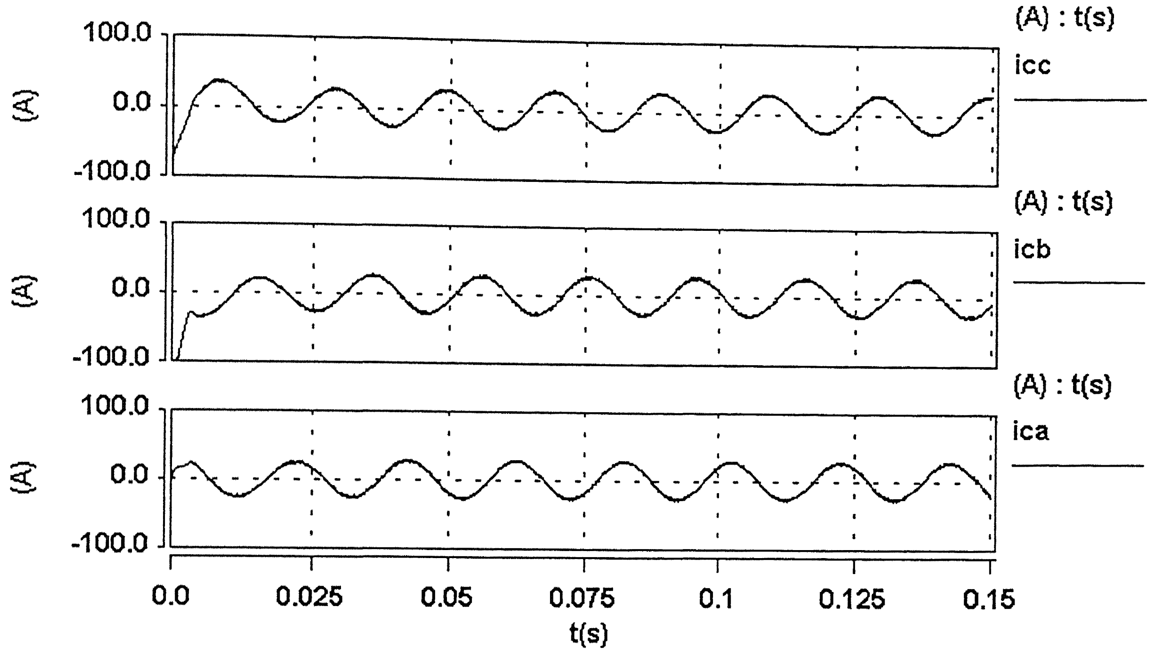

Fig. 4.11 Compensating current of three-phase for inductive load

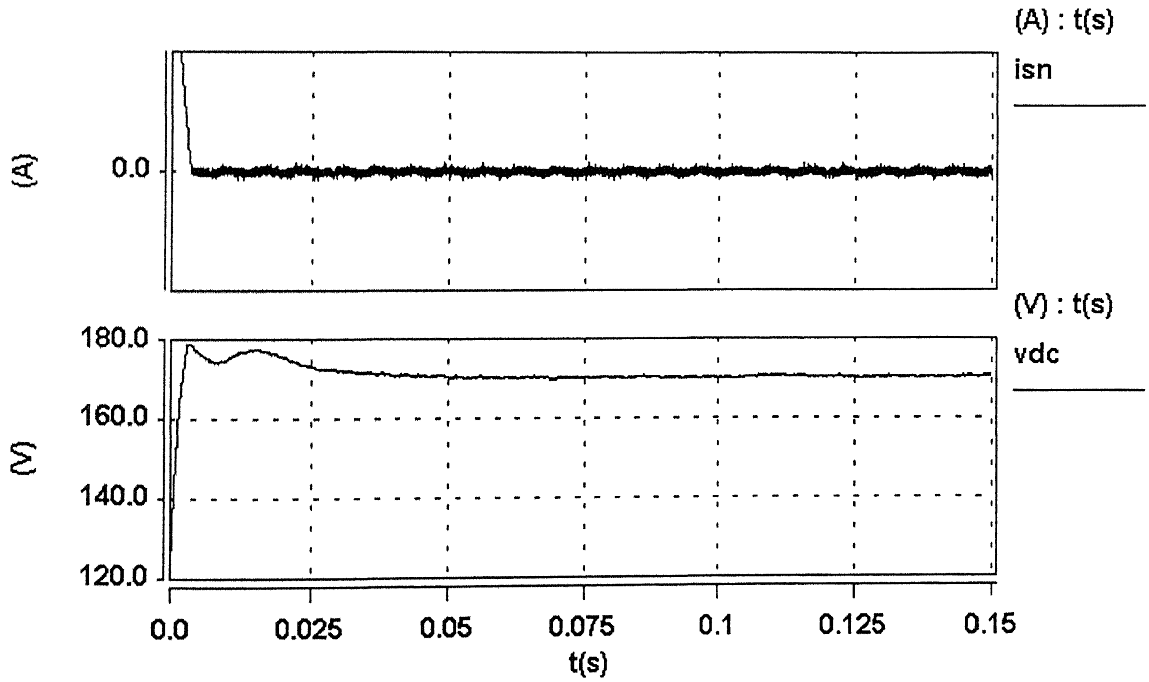

Fig. 4.12 Source side neutral current and dc link voltage

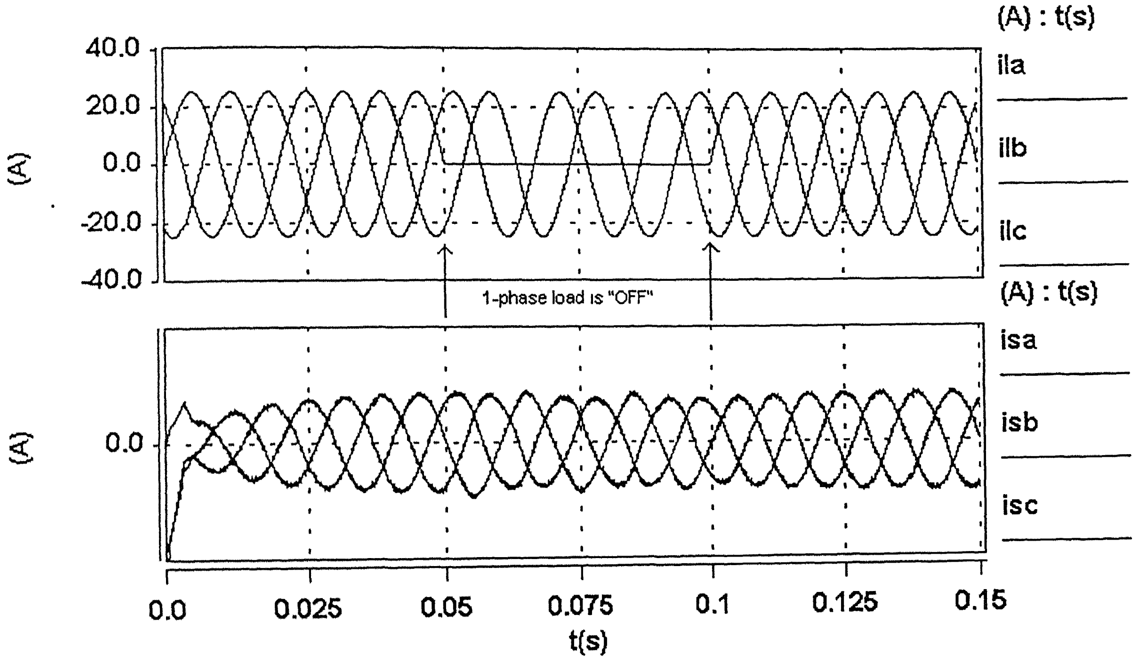

Fig. 4.13 Unbalance load current and source current

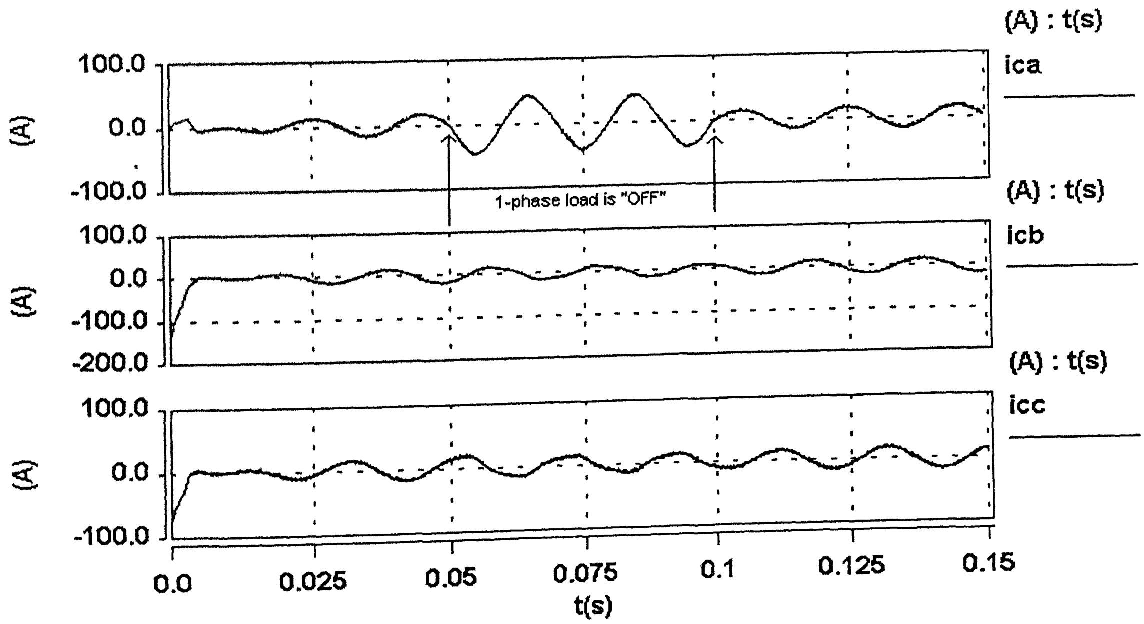

Fig. 4.14 Compensating currents

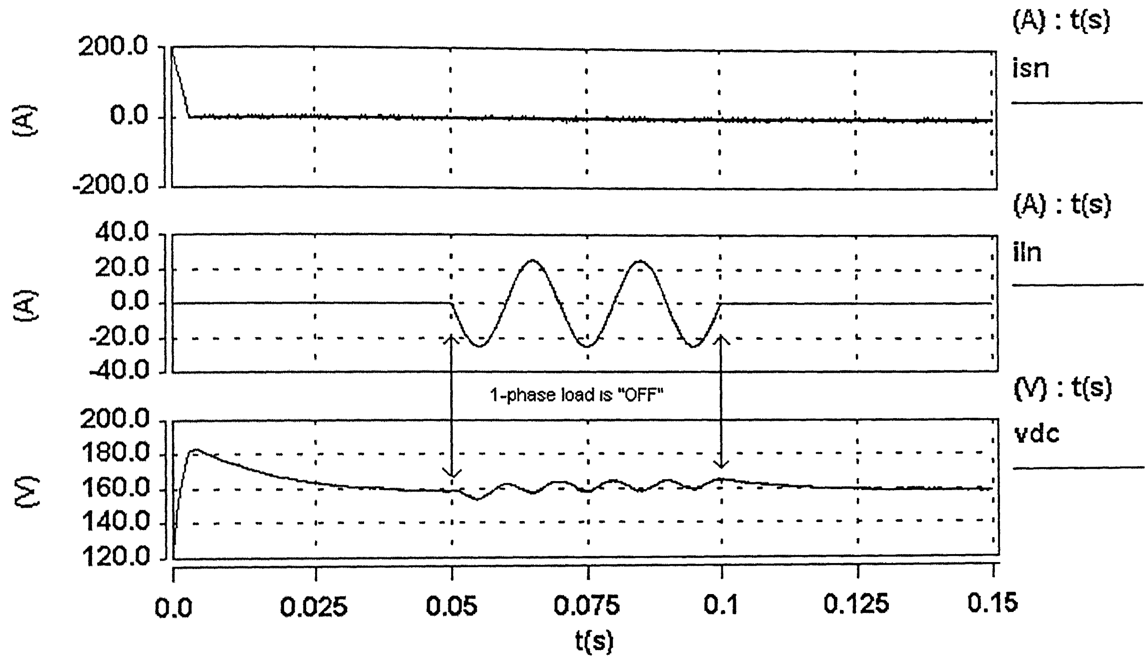

Fig. 4.15 Neutral current of source side and load side, dc link voltage

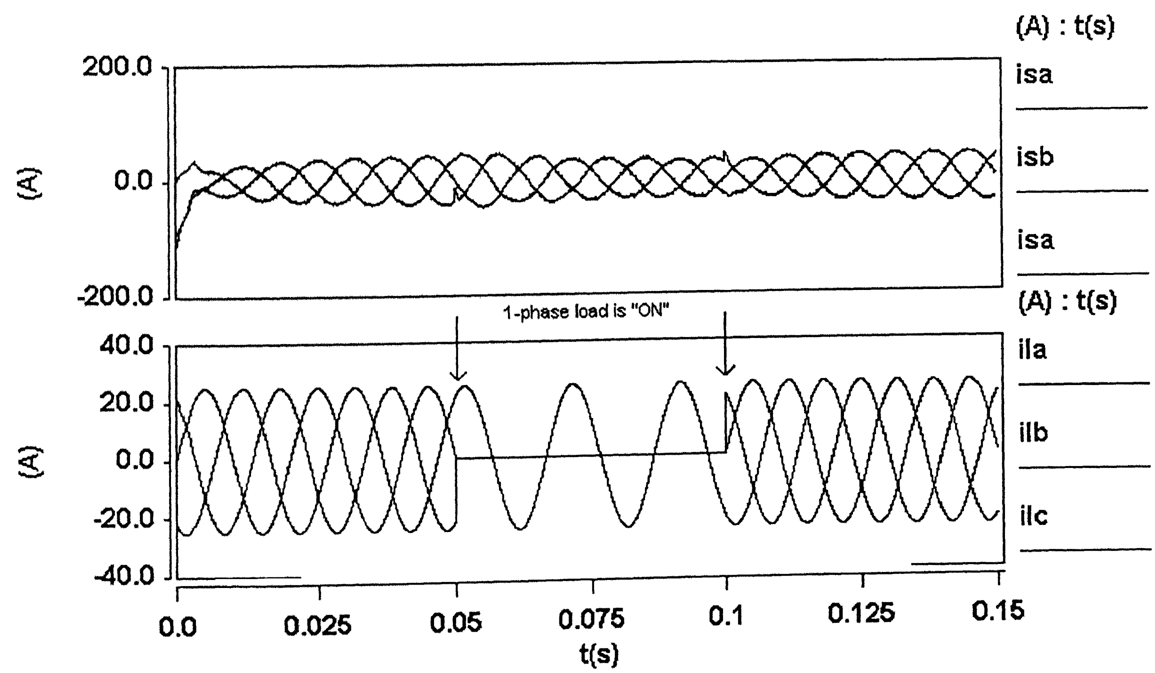

Fig. 4.16 Balanced source current and load current

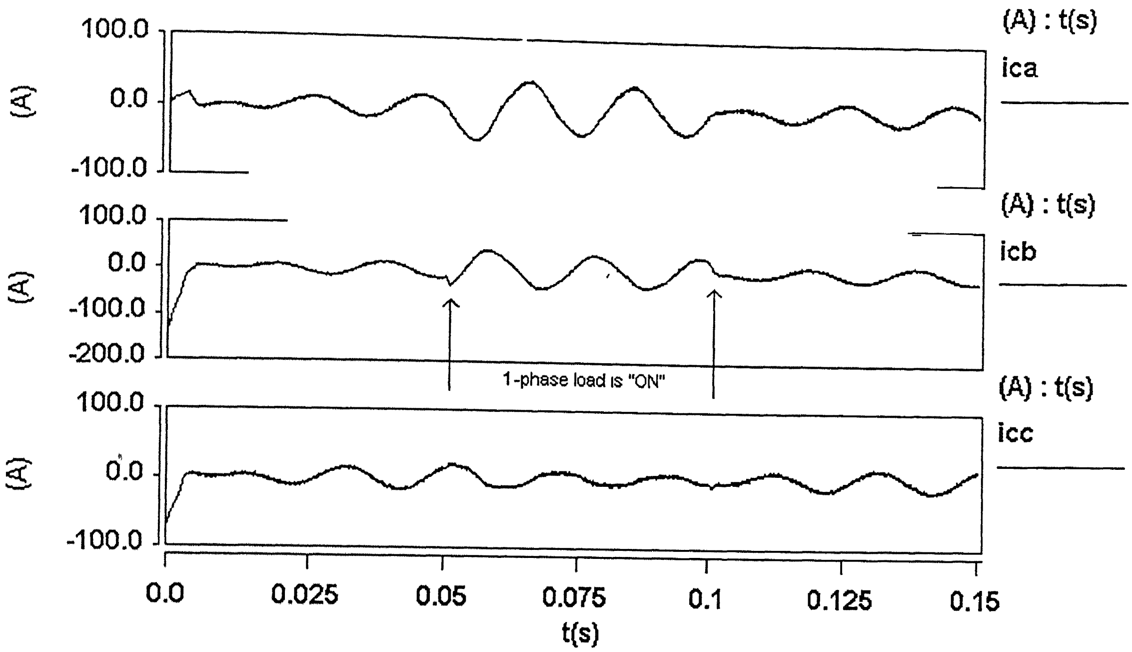

Fig. 4.17 Compensating currents

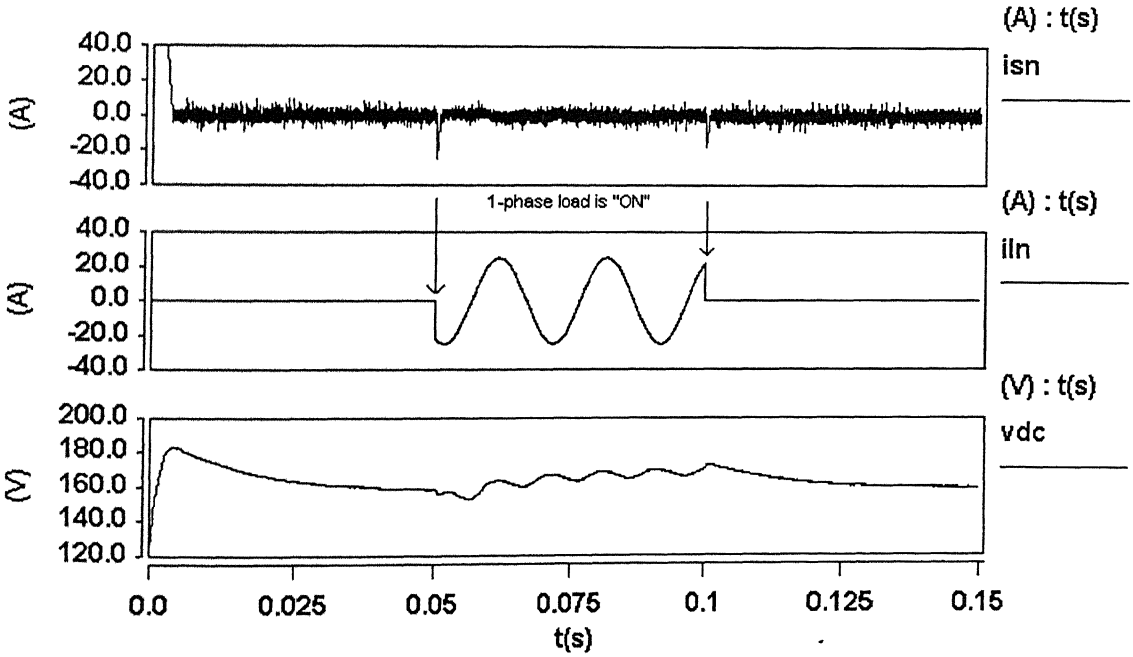

Fig. 4.18 Neutral current in the source side and load side and dc link voltage

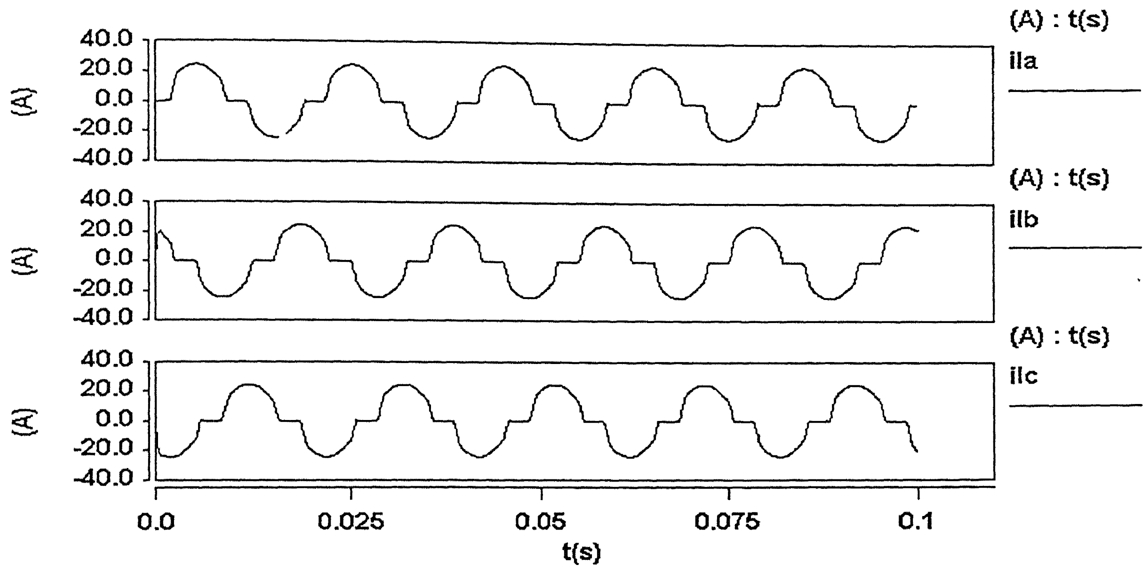

Fig. 4.19 Non-linear three-phase load current

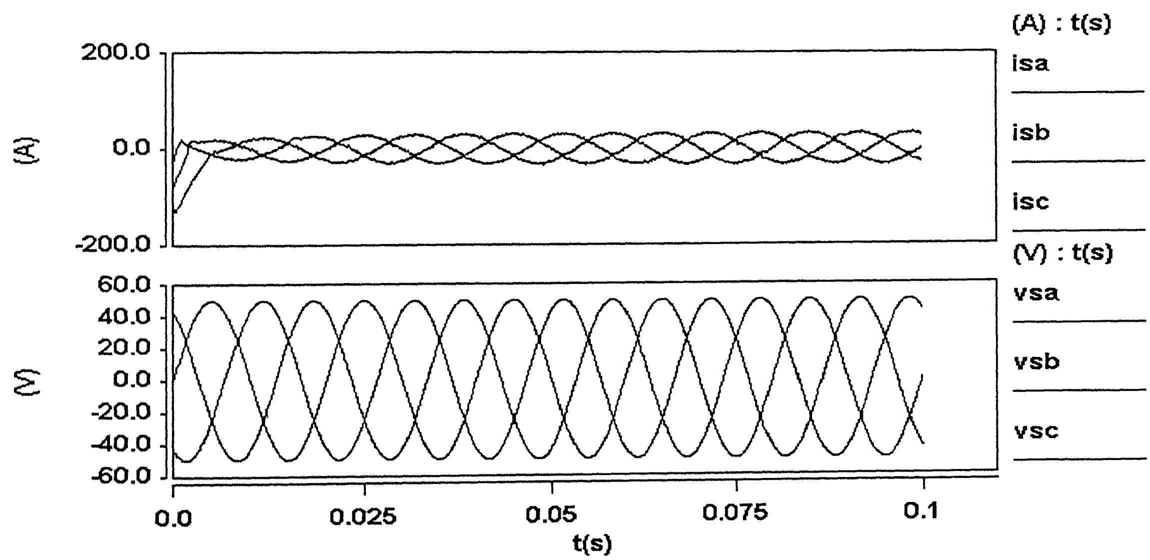

Fig. 4.20 Source current and source voltage

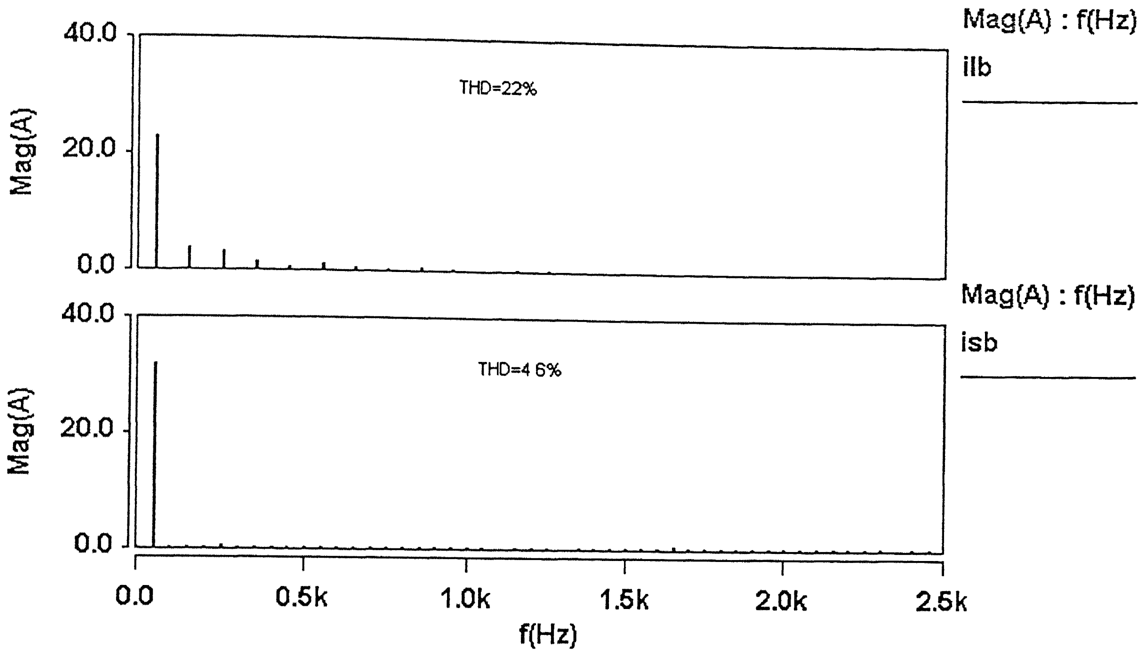

Fig. 4.21 Harmonics spectrum of load current and source current

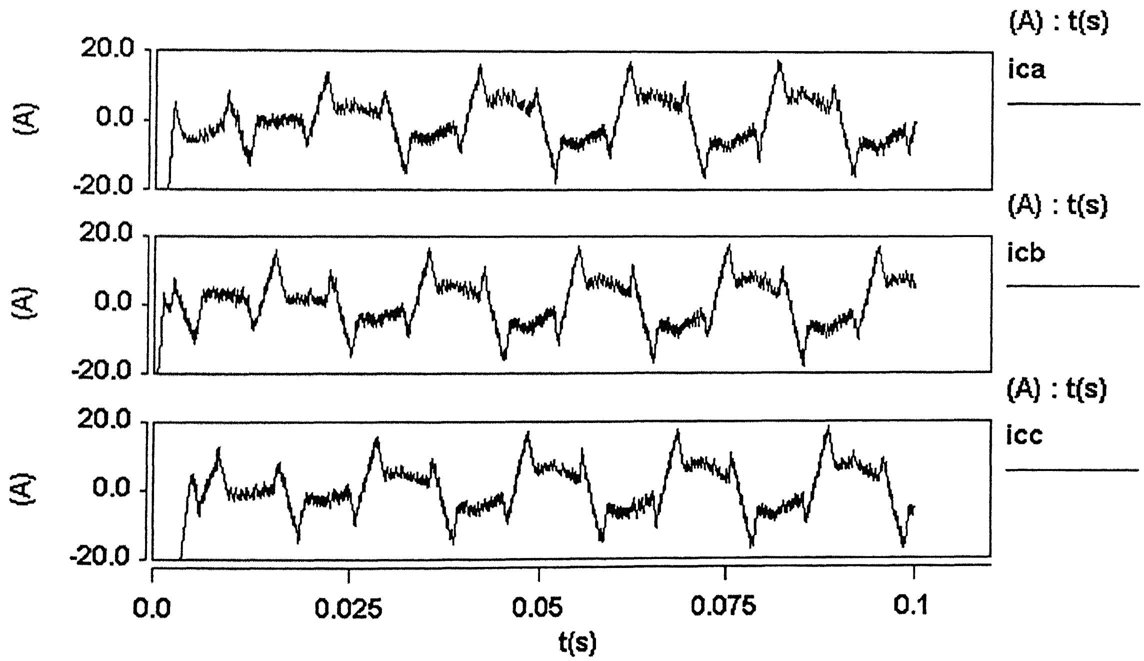

Fig. 4.22 Compensating currents

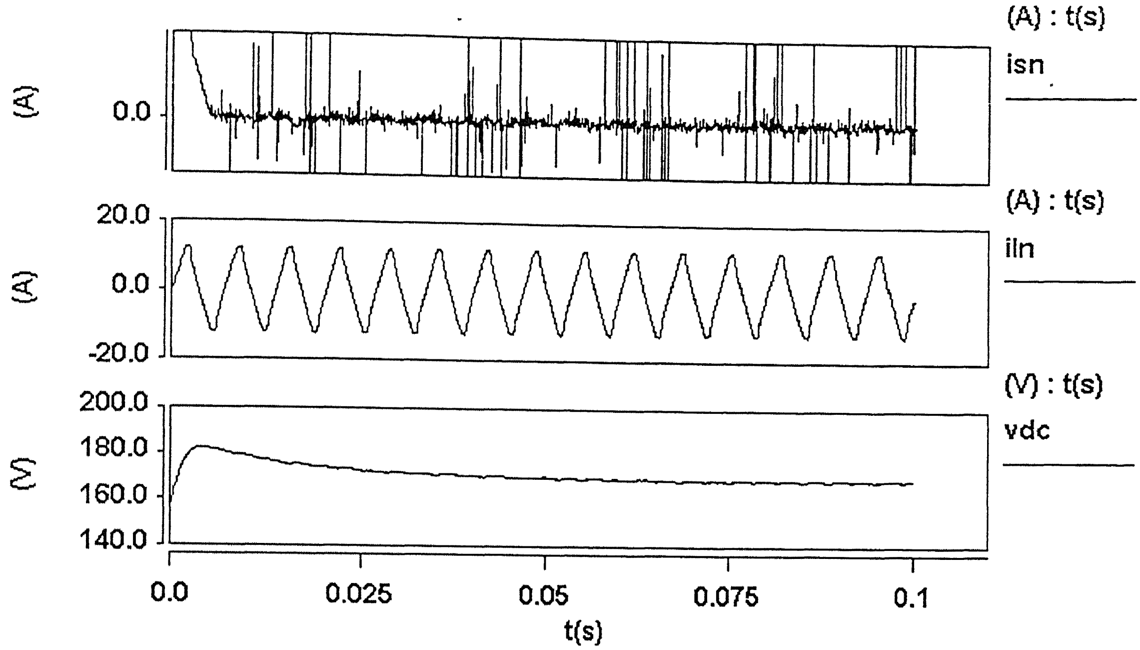

Fig. 4.23 Neutral currents and dc link voltage

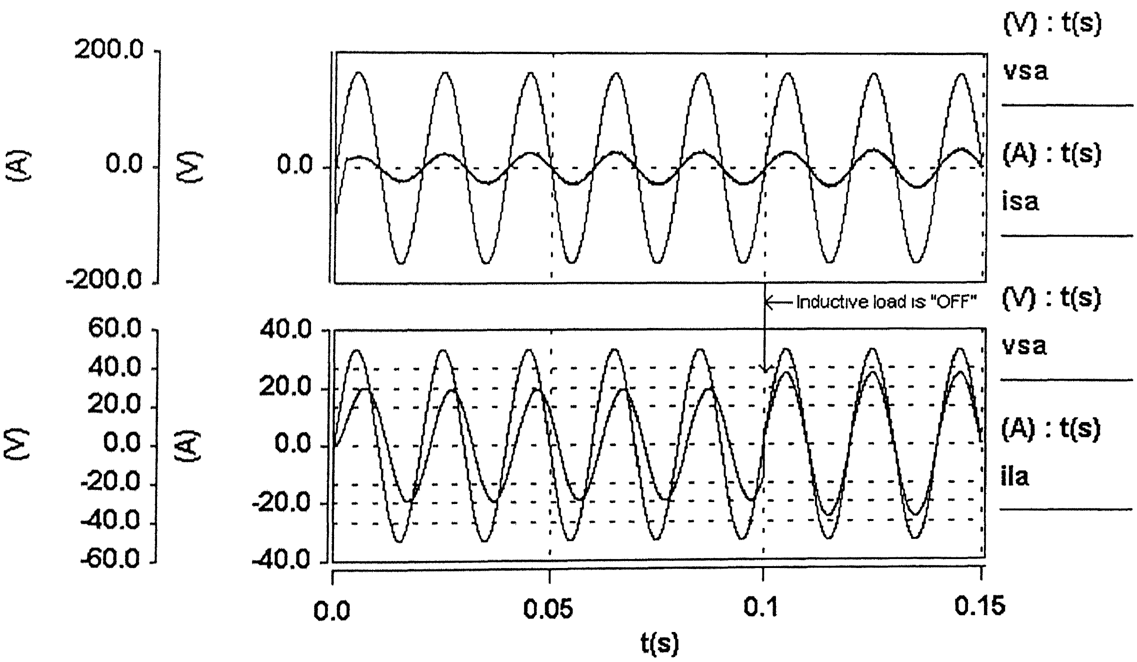

Fig. 4.24 Source voltage, source current and load current

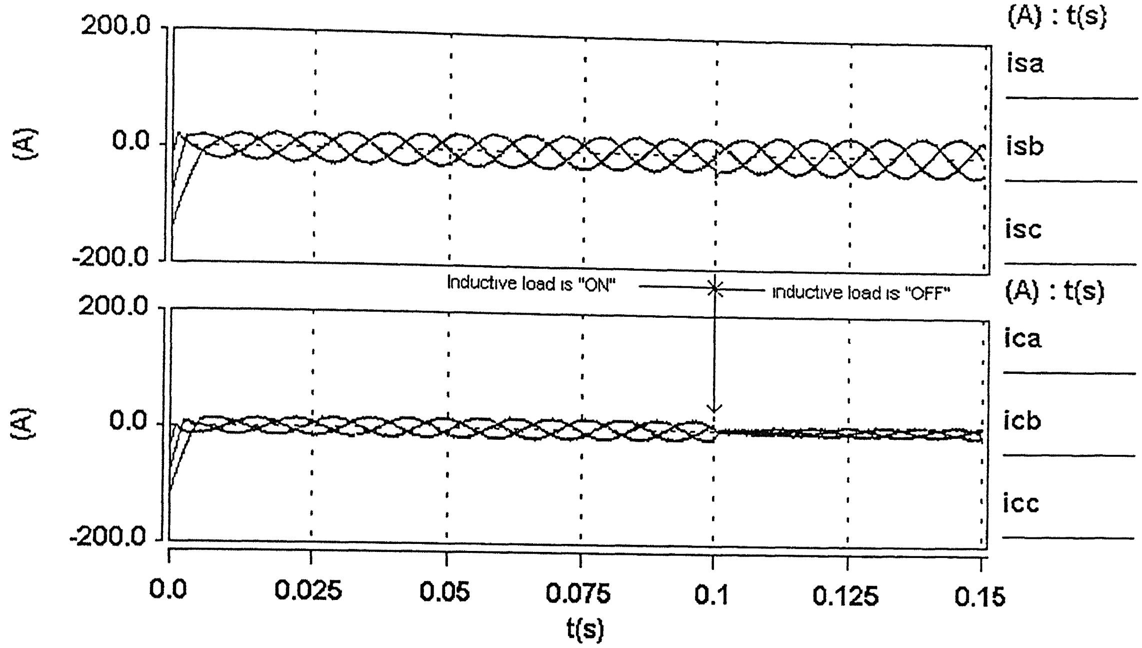

Fig. 4.25 Source current and compensating current

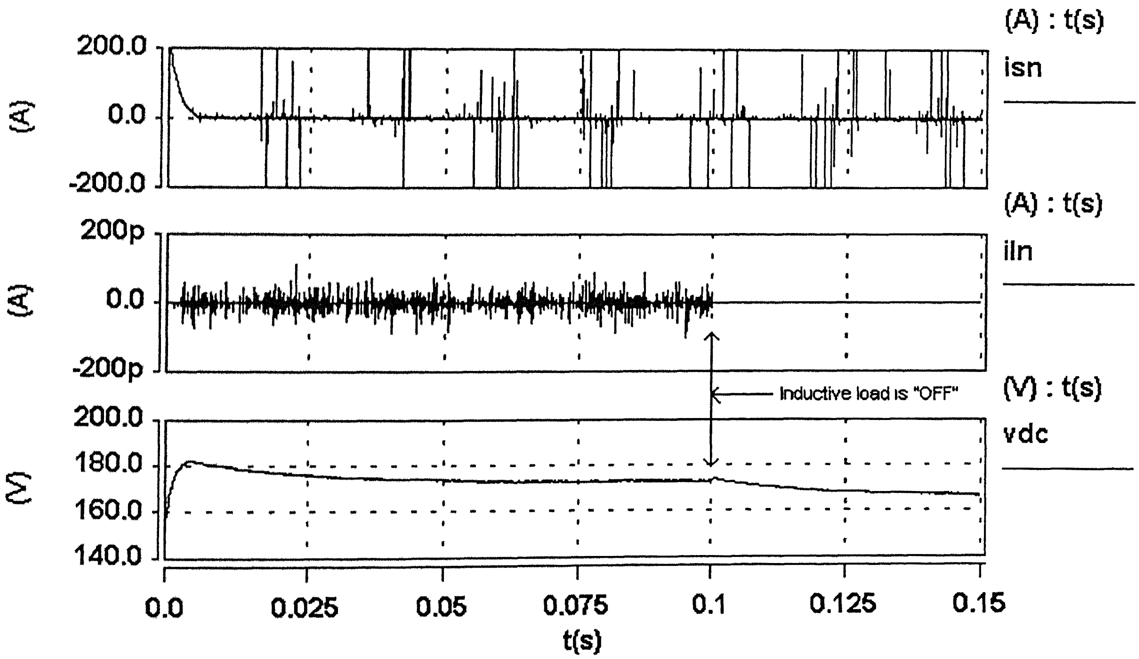

Fig. 4.26 Neutral currents and dc link voltage

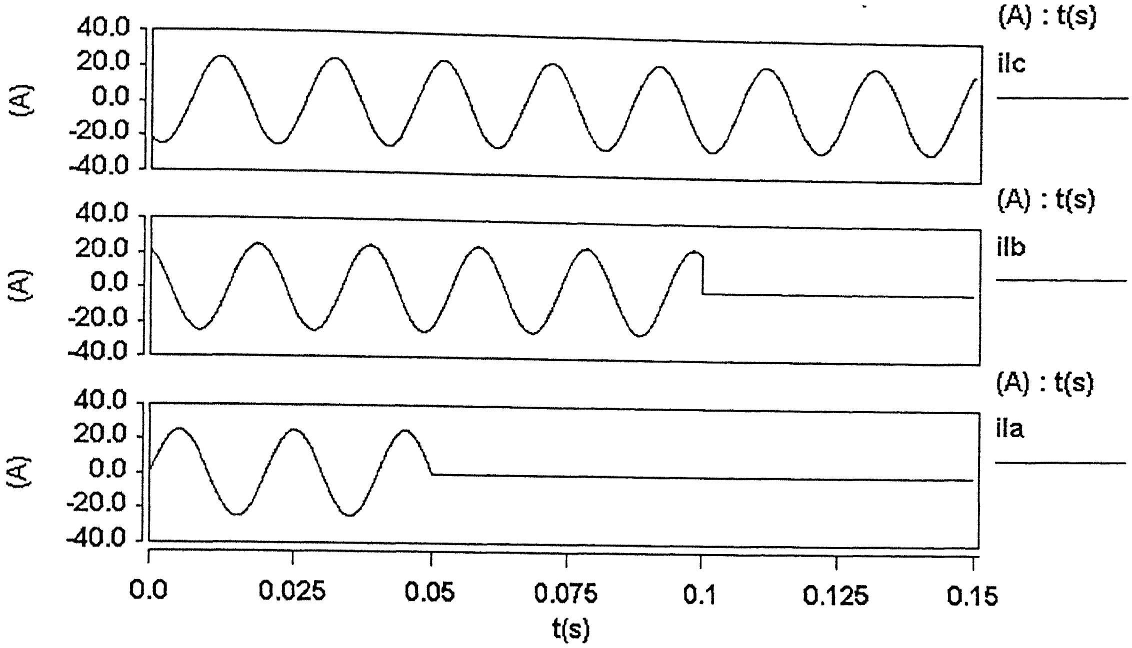

Fig. 4.27 Unbalanced load current of three-phase system

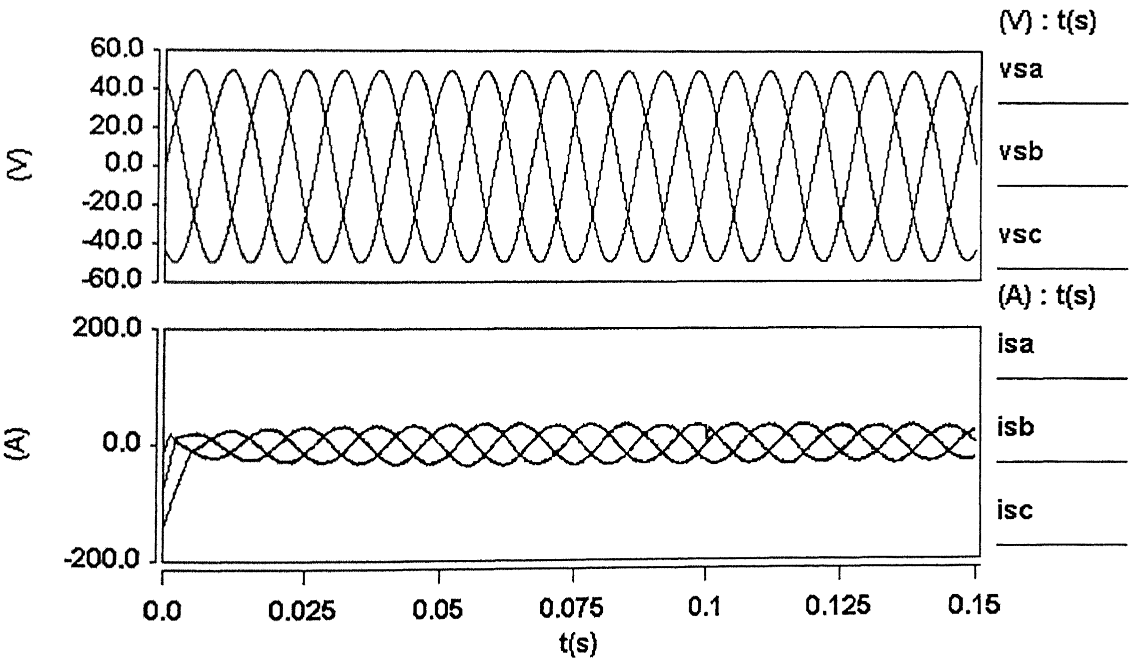

Fig. 4.28 Source voltage and source current

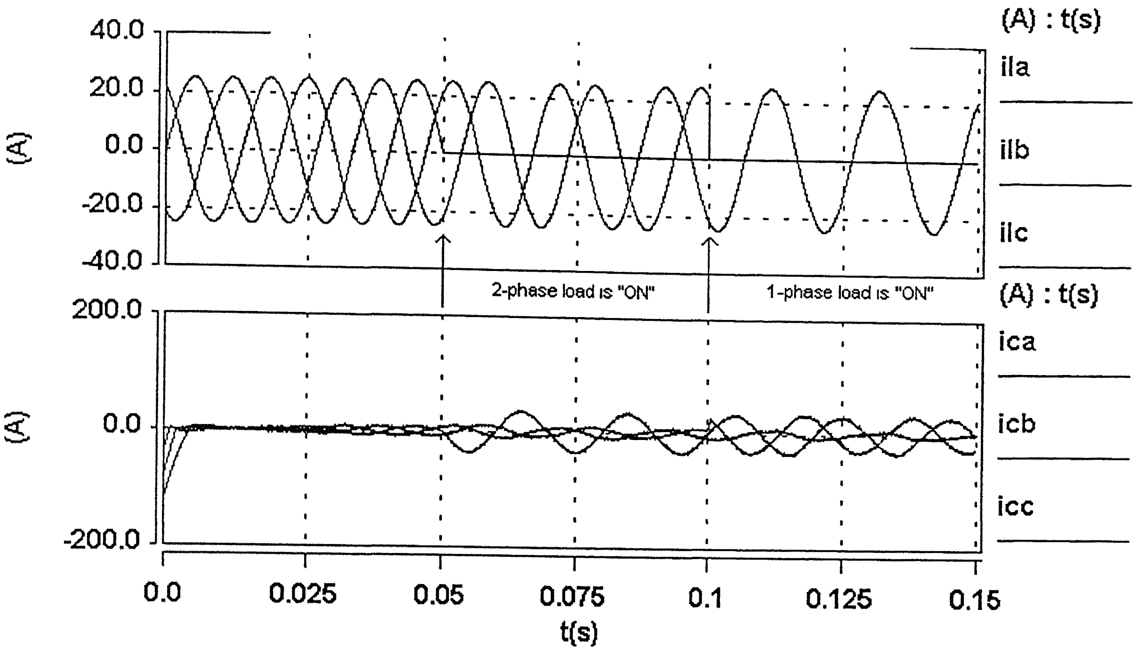

Fig. 4.29 Load current and compensating current

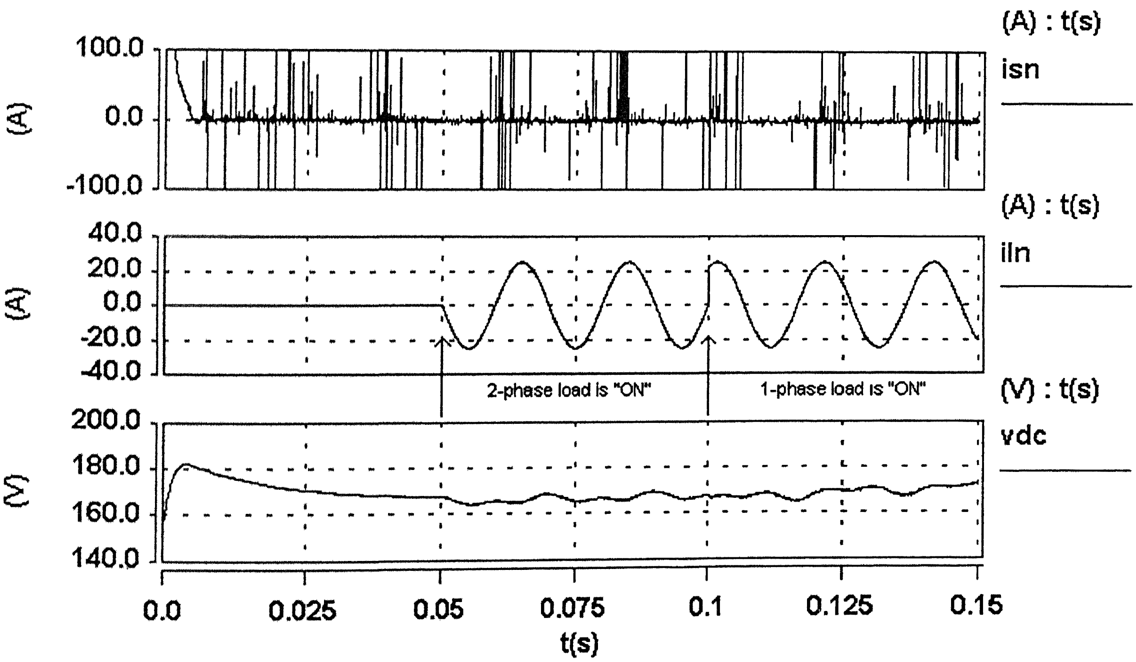

Fig. 4.30 Neutral current and dc link voltage

4.8 Conclusion

Various active power filters suitable for three phase four wire system have been discussed. Two active power filter configurations, namely, four-leg VSI and split capacitor VSI have been studied in detail. Both the systems have been simulated using SABER simulator. The steady state and transient simulation of APFs show their effectiveness in compensating balanced and unbalanced loads. The APFs also make the input power factor unity with zero supply neutral current.

CHAPTER 5

HIGH POWER ACTIVE POWER FILTER FOR LINEAR AND NON-LINEAR LOADS

5.1 General

At high power, efficiency of Active Power Filters (APF) is less due to significant switching loss. Therefore, current control in high power application faces difficulty. A combination of high power low frequency devices and low power high frequency devices has been presented here with superior performance in VAR compensation and harmonic filtering. A high power converter (main converter), which consists of high power low switching frequency devices, is operated at low frequency to deliver the VAR requirement of the load. Another converter (auxiliary converter), which consists of low power high frequency devices is operated in parallel to it. The auxiliary converter eliminates the harmonics produced by the main converter and that of the load such that the utility current THD is less than the specified value in IEEE-519 standard for a particular level of current. Additionally, the power rating of the auxiliary converter is low as it does not handle the reactive load current. The main converter is a three level Neutral Point Clamped (NPC) converter which employs GTOs as switching device.

To show the usefulness of the control scheme, an extensive simulation study has been carried out using SABER simulator.

5.2 Power Circuit Configuration of the Proposed APF

A three phase three wire star connected utility is considered. The combined Active Power Filter is connected in parallel to the load. The main converter is a neutral point clamped

(NPC) three level inverter (Fig. 5.1), with high power low frequency devices (like GTO). By keeping the switching frequency to fundamental only, the switching loss is minimized and the full utilization of the current carrying capability of switching devices is realized. Thus the main converter can carry high reactive power demand of the load. The auxiliary converter consists of low power high frequency devices (like IGBT), controlled by hysteresis current control technique. It eliminates the main converter current harmonics and the load current harmonics from flowing to the utility current by high switching frequency operation. The two converters share the same dc link capacitor leading to a compact structure.

To avoid circulating currents between the two converters, the auxiliary converter is connected in parallel to the load as well as main converter with an isolation transformer. This prevents the circulating reactive current between the two converters even though they share the common dc link.

The effects of both linear and non-linear loads have been studied. The non-linear load under study is a phase controlled rectifier, which simultaneously produces VAR and large current harmonics. Fig. 5.1 shows the power circuit configuration with a NPC three level inverter as the main power converter of the parallel active power filter scheme, which will be termed as Neutral Point Clamped converter based Active Power Filter (NPC - APF).

As found from Fig. 5.1, half of each phase leg is split into two series connected switches and mid-point of each pair is connected by diodes (like D_{f1} and D_{f4} in phase A) to the midpoint N of the two capacitors.

Here the voltages across the switches are only half of the dc link voltage. Fig. 5.2a shows the NPC converter output voltage for phase A. When the voltage is positive, switches 1, 1m conduct, and when the voltage is negative, 4, 4m conduct. When the phase voltage is connected to the neutral point N (i.e., zero voltage), switches 1m, 4m conduct. The present NPC converter topology leads to doublng the number of switches in addition to two extra clamping diodes. However, doubling the number of switches with same voltage rating makes the dc voltage rating to double, and this increases power handling capability of the converter. It is essential to ensure that the two capacitors are charged to same voltage because unequal voltages will generate even harmonics. A simple chopper circuit (with two switches and an inductor of 10 mH) has been used to maintain the charge balanced between two capacitors (shown in Fig. 5.1). The filter inductance (L_m) for the main converter is 10 mH and that for the auxiliary converter (L_a) is 4 mH. Each dc link capacitor (C_1 and C_2) is 1000 μF.

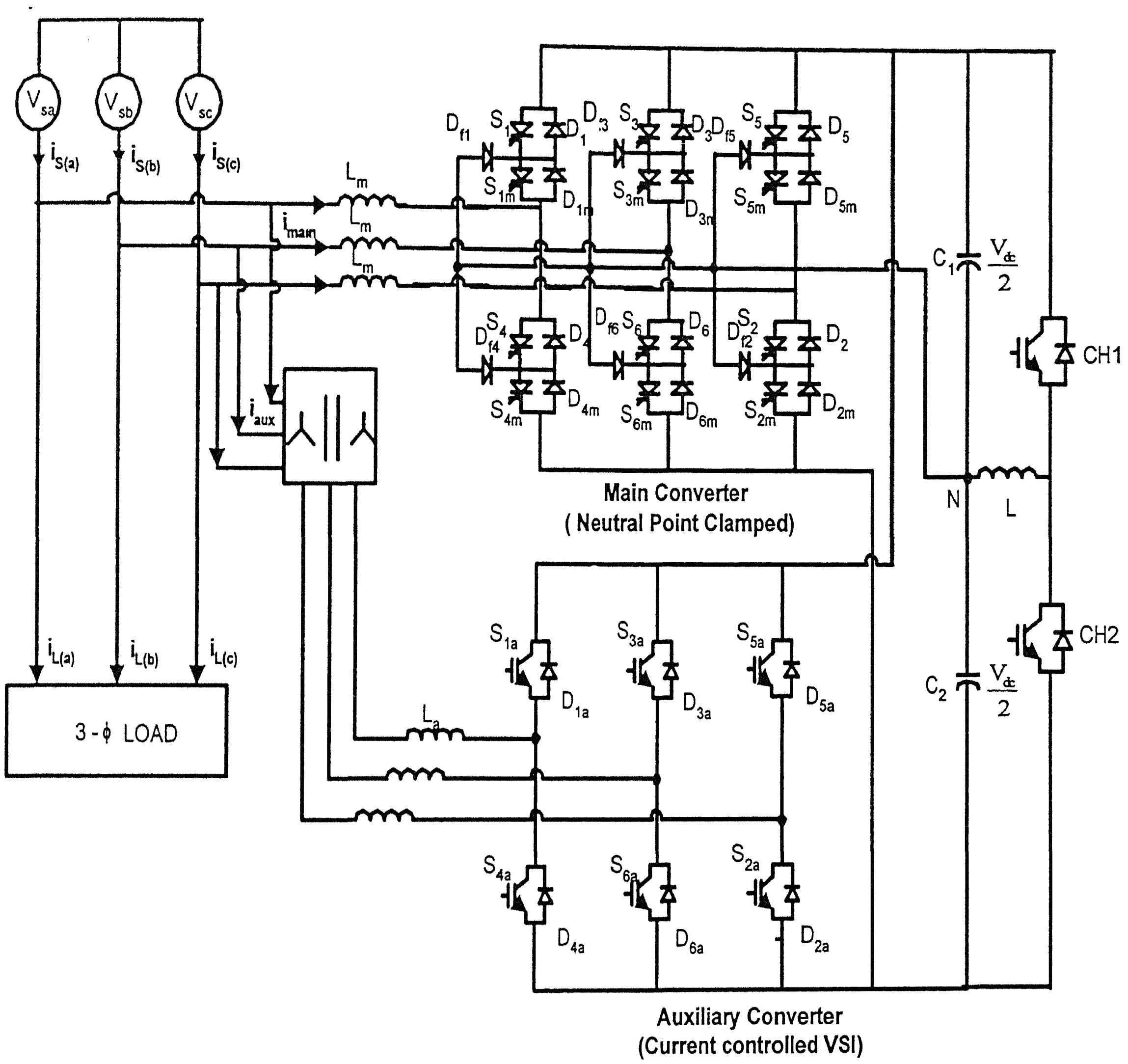

Fig. 5.1 Power circuit configuration of NPC-APF

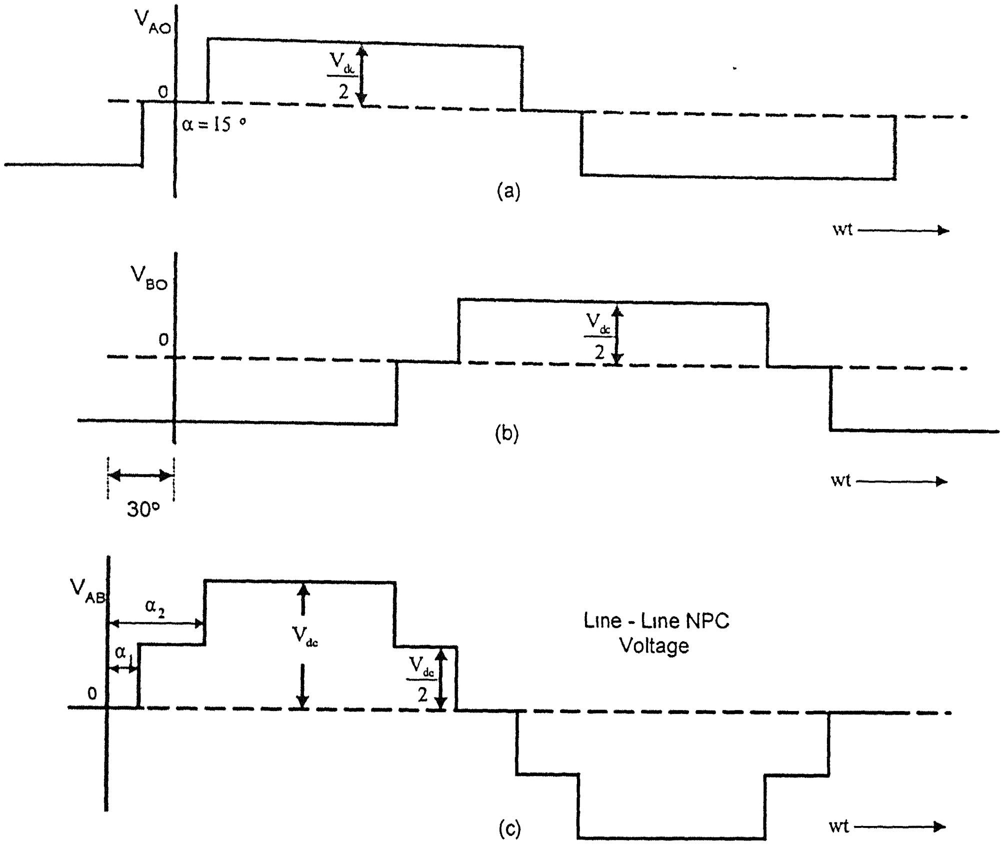

Fig. 5.2 Typical phase and line voltage of NPC converter and 6 - step converter.

a) Phase to neutral voltage of NPC converter (V_{AN})

b) Phase to neutral voltage of NPC converter (V_{BN})

c) Line – Line voltage of NPC converter (V_{AB})

5.3 Control Strategy of the Proposed APF

5.3.1 Equivalent circuit representation

The per phase equivalent circuit of main converter for fundamental frequency is shown in Fig. 5.3. Since the main converter is responsible to supply the fundamental VAR requirement of the load, the main converter current is compared with the fundamental reactive load current to generate a reactive current error.

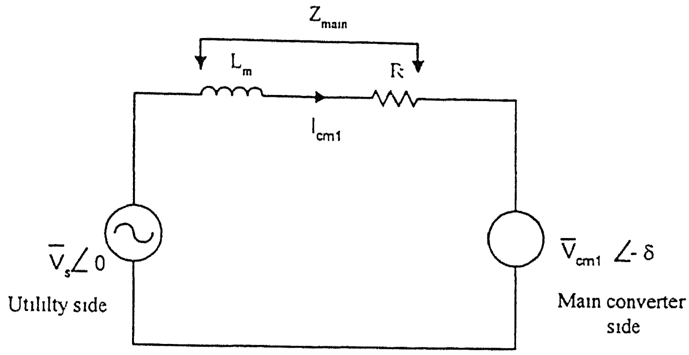

Fig. 5.3 Per phase equivalent circuit of the main converter with fundamental frequency voltage and current

The reactive current error is processed through a PI controller to control the voltage delay angle δ of the main converter for indirect current control. The change of δ leads to a change of active power flow between the utility and the main converter. Thus, the dc link voltage undergoes variation with change of δ. Since, V_{cm1} (converter fundamental voltage) is a function of V_{dc}, δ variation leads to change of V_{cm1}.

Hence, the main converter current varies according to the following equation.

$$I_{cm1} = \left(\frac{V_s - V_{cm1}\angle -\delta}{Z_{main}} \right) \qquad \ldots \qquad (5.1)$$

where, V_s is the supply voltage, Z_{main} is the impedance of the inductor (L_m) connecting the main converter to the supply, and I_{cm1} is the fundamental rms current of the main converter. With the information of δ, the modulating signals are adjusted to trigger the main converter switches.

5.3.2 Control of main and auxiliary converters

The complete system control block diagram for the proposed NPC-APF converter has been given in Fig. 5.4. It is desirable that the utility should supply only the active component of load current and the loss component of the converters at unity power factor. Therefore, the supply current should be always in phase with respective phase voltage. In ideal case, angle δ is supposed to be zero, as the main converter current caters only the load reactive current, which is at quadrature with the supply voltage. However, because of the converter losses, the capacitor voltage tends to fall and requires small amount of active current from the supply to maintain the charge. So the angle δ acts as a measure of converter losses and a control signal proportional to δ is added with the active component of load current ($|i_{Lact}|$) to determine the reference magnitude of the source current. This amplitude, multiplied by a sin-template (in phase with respective utility phase voltage) gives the reference utility current (i^*_s) for the respective phase.

For non-linear loads, a band pass filter is used to extract the fundamental component of load current and its active and reactive components are separated out. The reactive component of fundamental load current ($|i_{Lreact}|$) is compared with the reactive component of the main converter current ($|i_{main\_reactive}|$) and the error is processed through a PI controller. The output of the controller acts as the information δ (for indirect current control) and modulating signals of the main converter are modified accordingly.

Inverter with low impedance and fast response tends to be overloaded in case of transient situation. So, for the start-up, the auxiliary converter is initially not triggered. When the main converter current reaches a steady value and the VAR of the load is supplied locally

from the main converter, the utility supplies the active component of currents and some higher order harmonics. After the auxiliary converter is switched on, the higher order harmonic currents are supplied from the auxiliary converter and the utility supplies only the fundamental active component of current. The magnitude of the utility current reference is addition of two signal components, namely fundamental active load component of current ($|i_{Lact}|$), and a component which brings information about δ (for the loss component of the converters). This amplitude multiplied by appropriate sinusoidal template of each phase in the reference current generator produces utility current reference (i^*_s). The actual supply current (i_s) is then compared with i^*_s in a hysteresis controller and the output of the controller determines the switching of the auxiliary converter.

5.3.3 Control of dc link voltage and chopper control

In the present control scheme, the dc link voltage is not compared with a pre-specified reference. It automatically charges up or down according to the VAR requirement of the load. A chopper circuit is used to keep the two capacitors charged to equal voltage. Whenever, one capacitor overcharges with respect to the other, a circulating current flows from one capacitor to the other through an inductor of 10 mH, such that the two capacitors are brought back to equal voltage. The chopping frequency is 5 kHz.

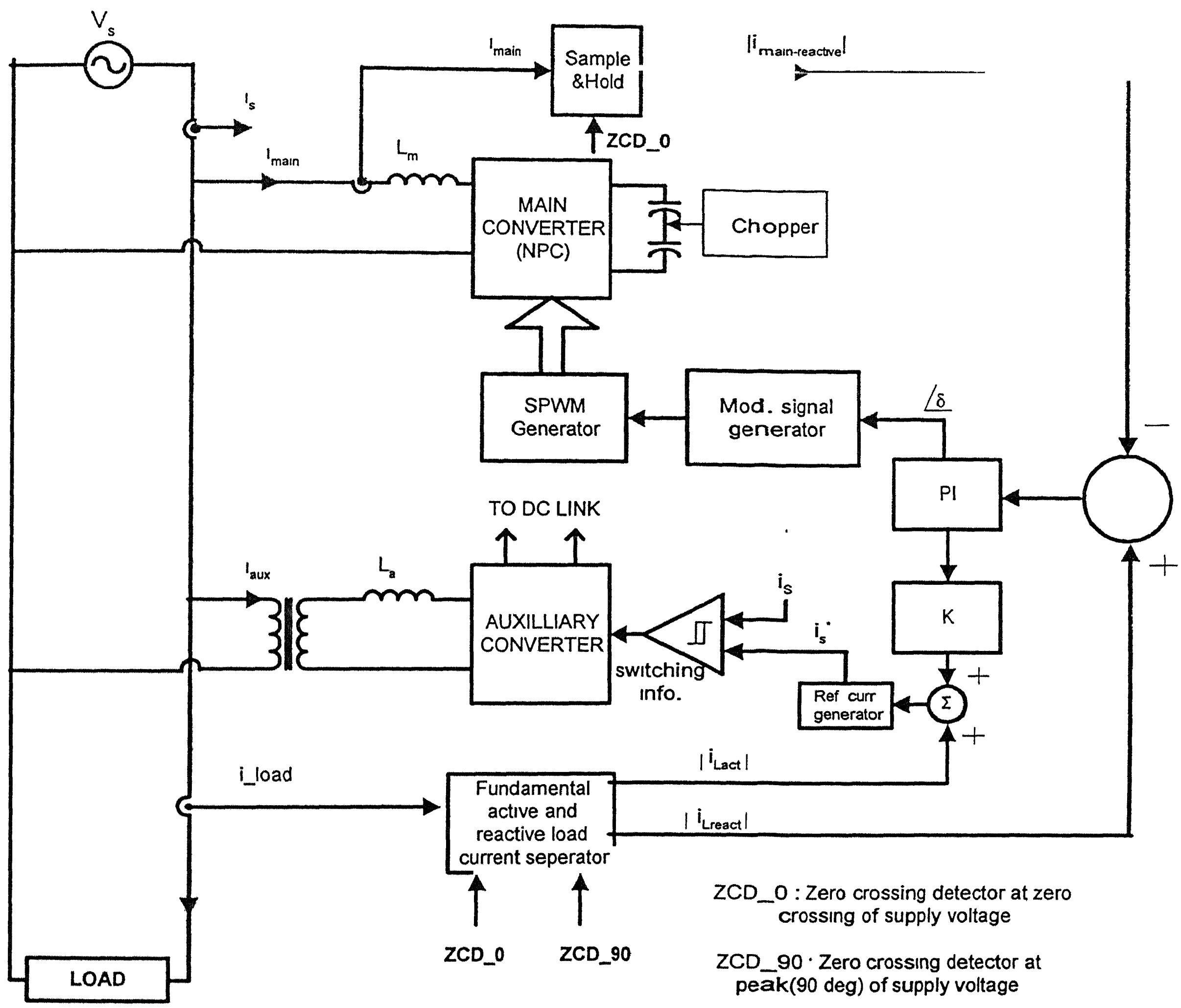

Fig. 5.4 Control block diagram of the proposed compensator scheme of NPC - APF

5.4 Simulation

Detailed simulation studies are carried out with SABER simulator to observe the performance of the proposed APF with the given control scheme. For the start-up process, the main converter is switched on, and after the current has reached steady state, auxiliary converter is activated.

5.4.1 Results and discussion of NPC-APF

VAR compensation

The load current has phase lag by 36° from voltage. For performance of NPC-APF as a VAR compensator, the result has been shown in the Fig. 5.5. The load current is changed from 127A to 100A, so the source current also changes, which has been shown in the Fig. 5.6. Variation of dc link voltage is shown in the Fig. 5.7.

Non-linear load compensation

Load current is 190A (peak) with a total harmonic distortion of 15% (Fig. 5.9). However, the source current is sinusoidal and in phase with the source voltage as shown in the Fig. 5.10. For the dynamic performance of APF, load current is decreased from 190A to 150A (Fig. 5.10) and the load harmonics is compensated up to THD=4.9% as shown in the Fig. 5.11. Variation of the dc link voltage and main and auxiliary converter currents are shown in the Fig. 5.12.

5.5 Conclusion

For high power applications, a parallel converter topology (NPC-APF) has been proposed. It has been observed that the main converter compensates VAR of the load

while auxiliary converter is dedicated for compensation of harmonic current generated by the main converter and the load. The dynamic performance of NPC-APF for non-linear loads has been simulated and found satisfactory. The input current THD is found to be as per the IEEE-519 standard.

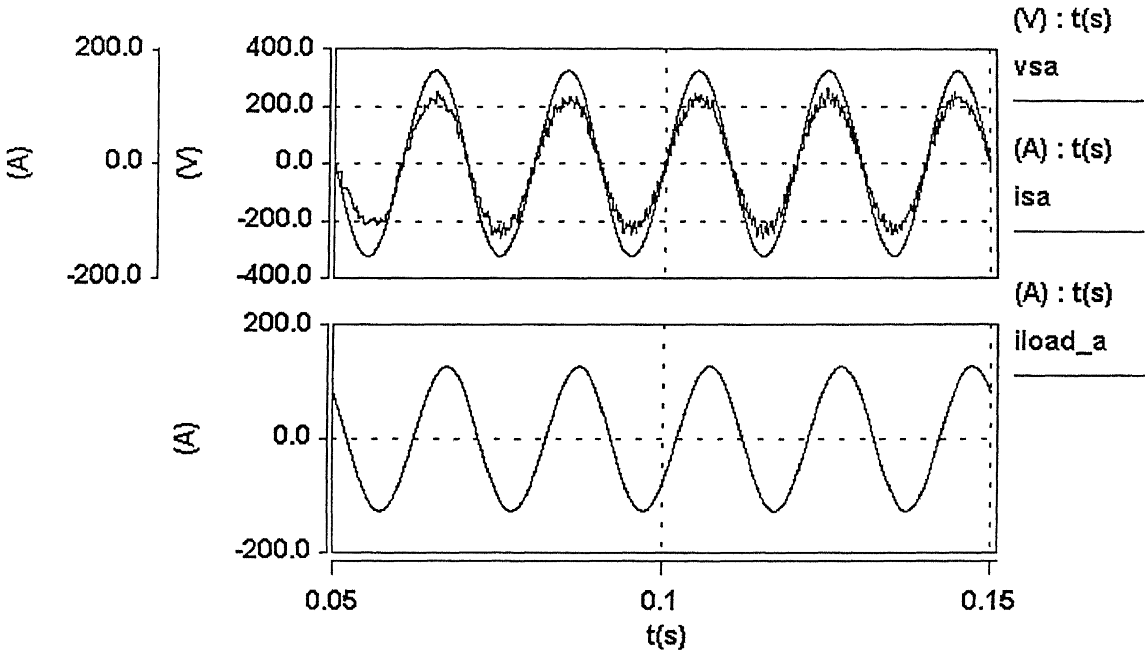

Fig. 5.5 Source current and load current

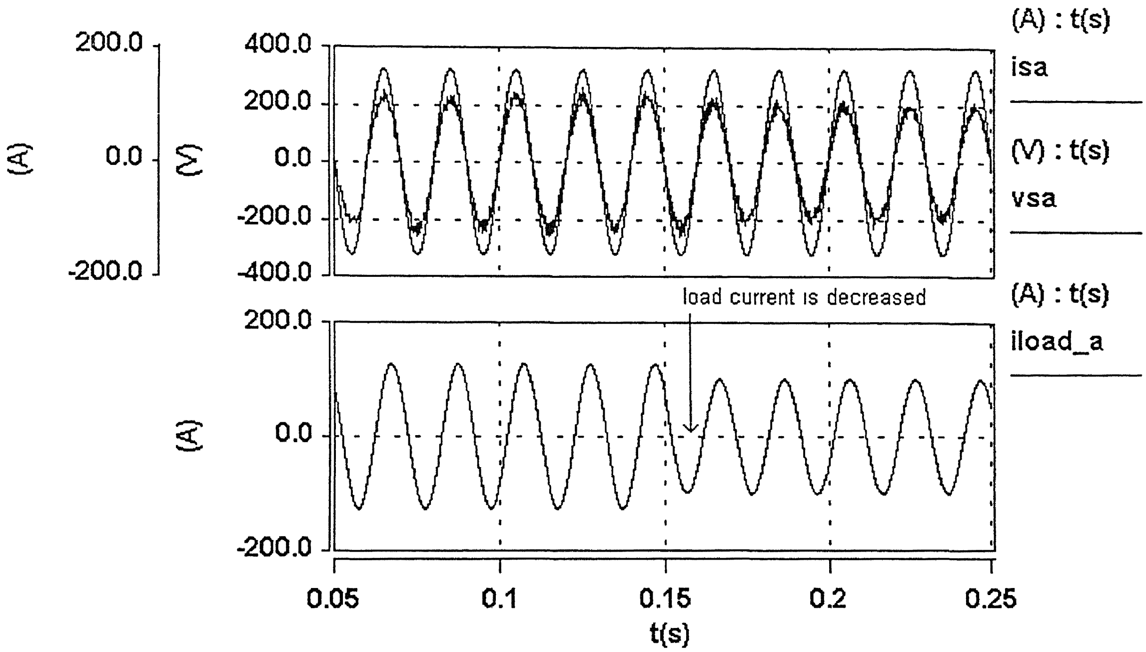

Fig. 5.6 Source current and load current under dynamic conditions

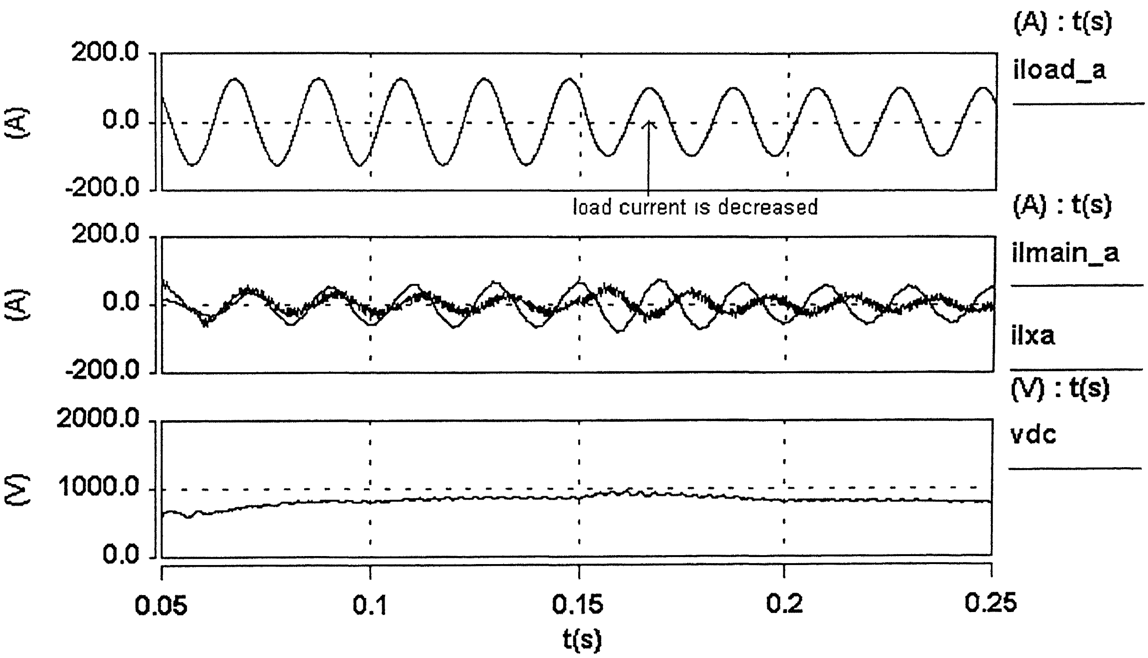

Fig. 5.7 Converter currents and dc link voltage

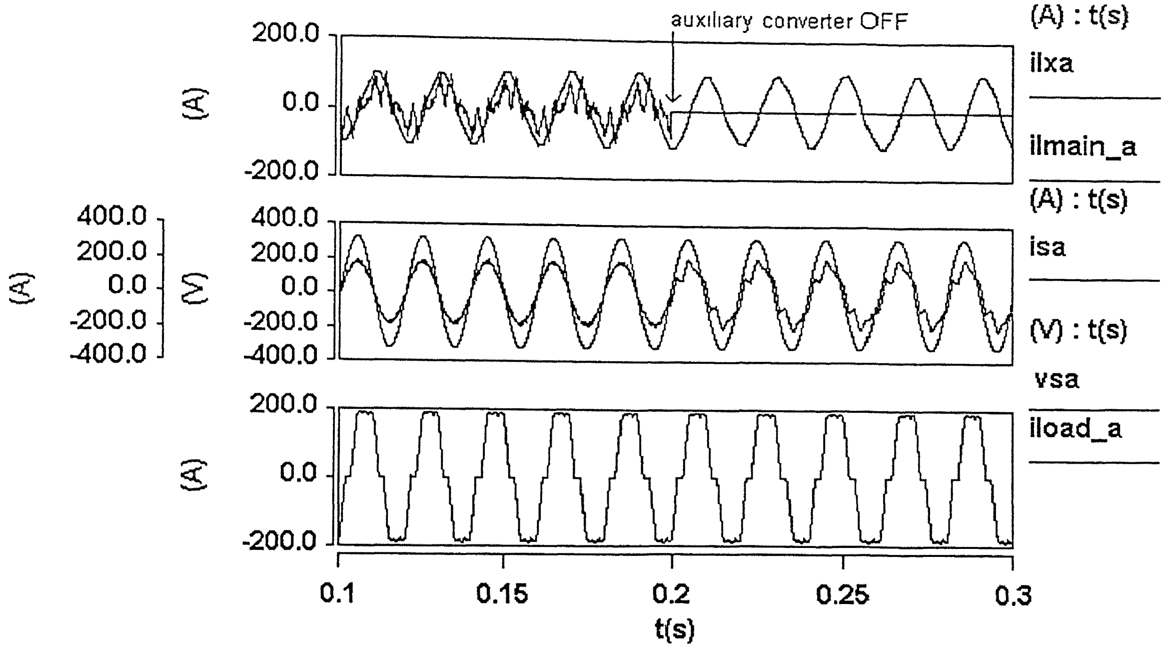

Fig. 5.8 Source current and load current

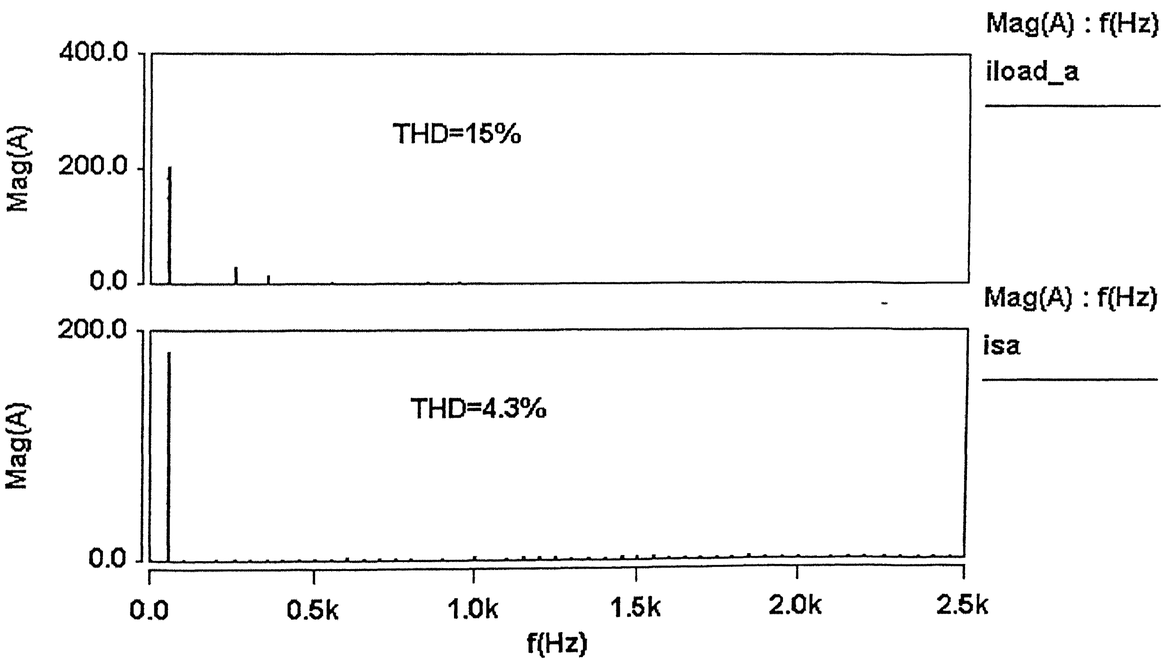

Fig. 5.9 Harmonics spectrum of load current and source current

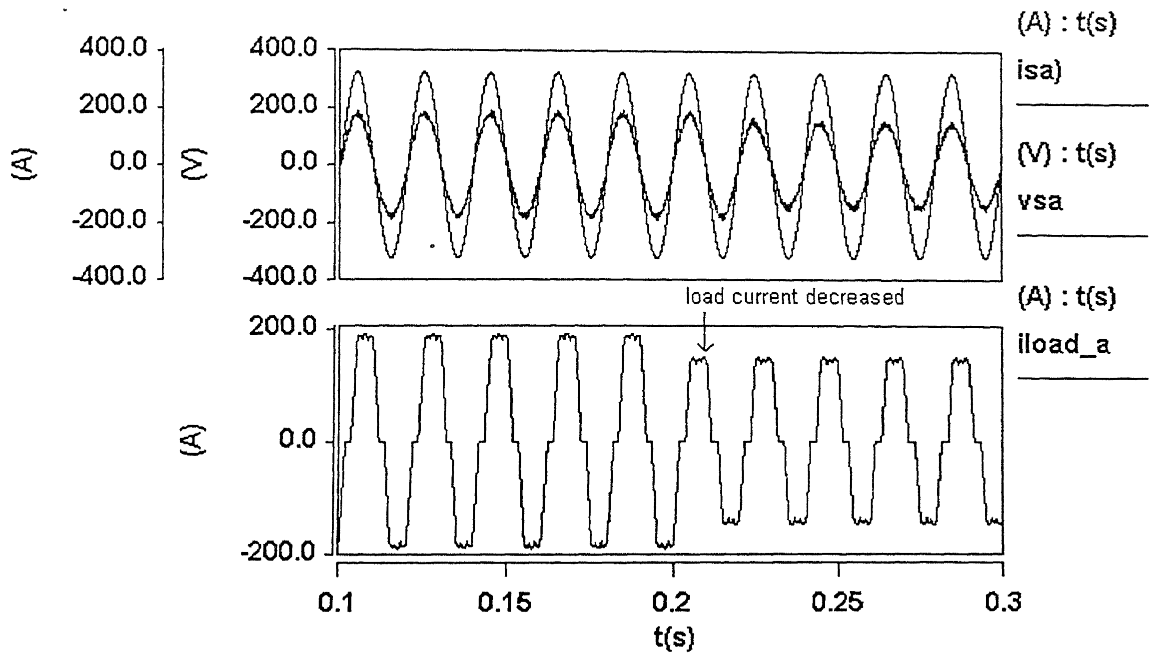

Fig. 5.10 Source current and load current

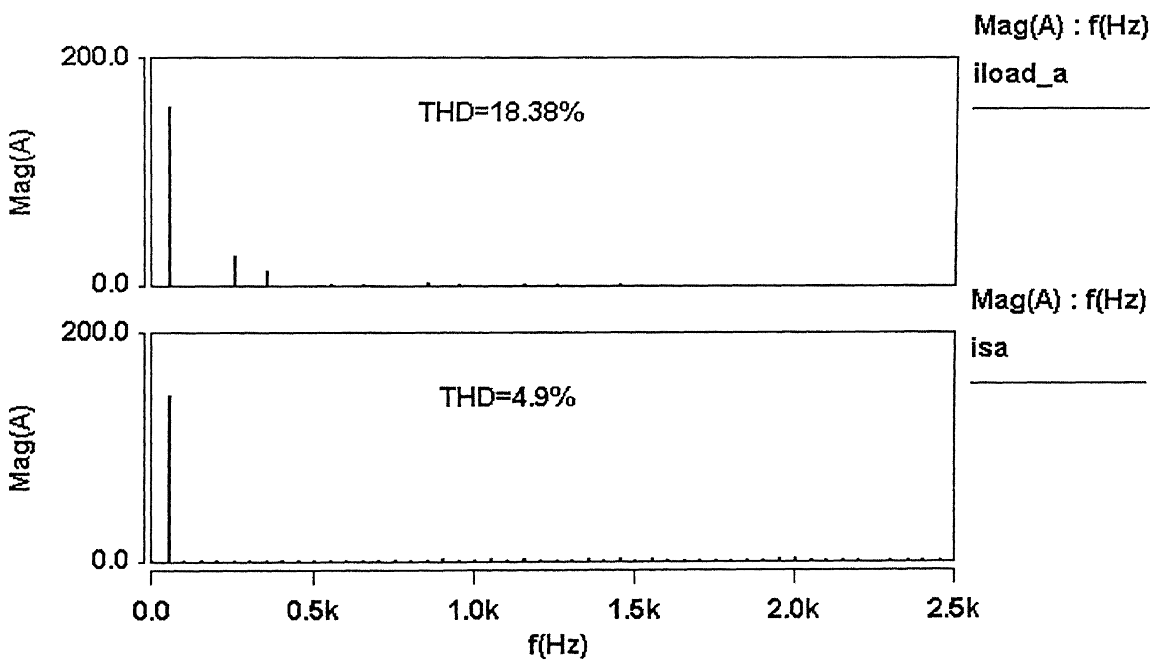

Fig. 5.11 Harmonics of load current and source current

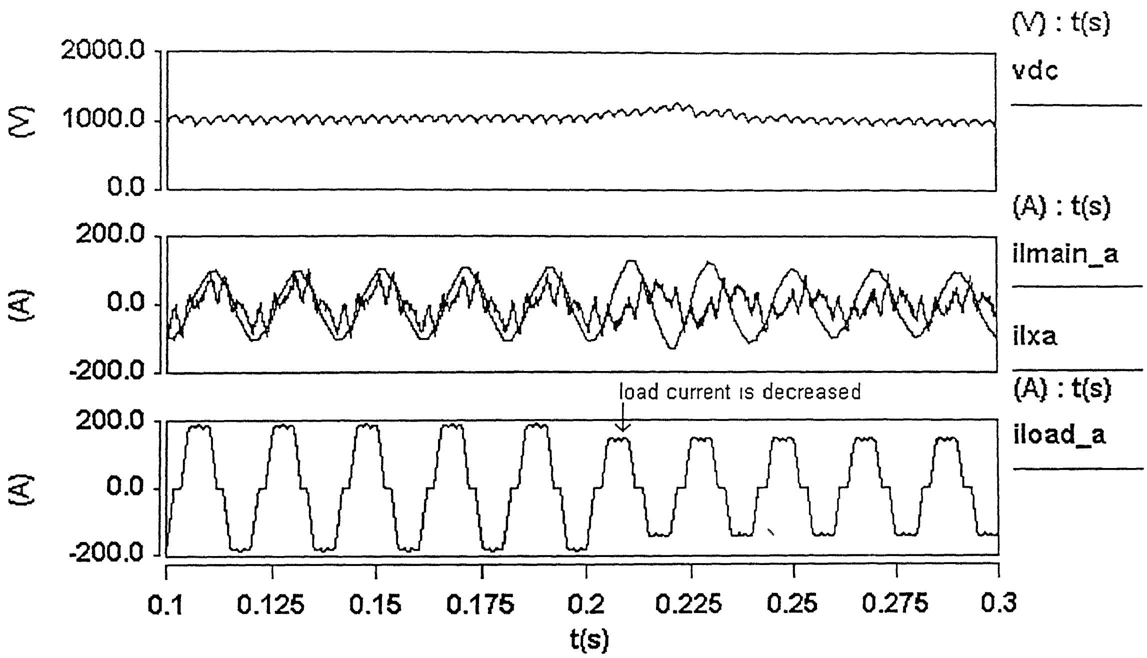

Fig. 5.12 Load current and dc link voltage

CHAPTER 6

CONCLUSIONS AND SUGGESTION FOR FUTURE WORK

6.1 Conclusion

Active power filters (APF) are widely used for harmonic filtering and VAR compensation in distribution system to improve power quality. Availability of fast and high power switching device has contributed significantly to the development of APFs. The present thesis reported the simulation and performance evaluation of single phase and three phase active power filters for linear and nonlinear loads. Initially, an active power filter topology for a single supply system has been simulated. This is followed by simulation of active filters for three phase, three wire system. Two topologies for active filters, namely four-leg inverter and split capacitor inverter, have been simulated for three phase four wire system. Finally, a parallel converter topology using a neutral point clamped (NPC) three level inverter in parallel with a current controlled active power filter (NPC-APF) for high power application has been reported. All APFs have been simulated for lagging power factor and nonlinear loads. The results show the effectiveness of the APFs in filtering out harmonic currents and compensating VAR of the load.

6.2 The scope for Future Work

The following suggestions are made for the future work in this area.

- Use of simpler control scheme for APF control
- Experimental investigation of the proposed APF topologies.

References

[1]. V. E. Wagner et al, "Effect of Harmonics on Equipment", IEEE Transactions on Power Delivery, vol.8, April 1993, pp 672-680.

[2]. A. Ghosh and A. Joshi, "A New Approach to Load Balancing and Power factor Correction in Power Distribution System", IEEE Transactions on Power Delivery, vol. 15, no. 1, Jan. 2000, pp 417-422.

[3]. L. Gyugyi and E. Strycula, "Active AC Power Filters", IEEE-IAS Annual Meeting Record 1976, pp 529-535.

[4]. J. Nastran, R. Cajhen, M. Seliger and P. Jereb, "Active Power Filter for Non-linear AC Loads", IEEE Transactions on Power Electronics, Vol.9, No.1, Jan 1994, pp 92-96.

[5]. S. Moran, "A Line Voltage Regulator/Conditioner for Harmonics-Sensitive load Isolation", IEEE-IAS Annual Meeting Record 1989, pp 947-951.

[6]. C. Chen and D. M. Divan, "Simple Topologies for Single-Phase AC Line Conditioning", IEEE-IAS Annual Meeting record 1991, pp 911-917.

[7]. R. M. Duke and S. D. Round, "The Steady State Performance of a Controlled Current Active Filter", IEEE Transactions on Power Electronics, Vol.8, No.3, April 1993, pp140-146.

[8]. H. Akagi, Y. Kanazawa and A. Nabae, "Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components Energy Storage Components", IEEE Transactions on Industry Applications, Vol.1A-20, No.3, May/June 1984, pp 625-630.

[9]. N. R. Raju, S. S. Venkata, R. A. Kagalwala and V. V. Sastry, "An Active Power Quality Conditioner for Reactive Power, Harmonic Compensation", IEEE-PESC Record 1995, pp 209-214.

[10]. L. Moran, P. Godoy, R. Wallace and J. Dixon, "A New Current control Strategy for Active Power Filters Using Three PWM Voltage Source Inverters", IEEE-PESC Record 1993, pp 3-9.

[11]. C. A. Quinn, N. Mohan and H. Mehta, "A Four Wire Current Control Converter Provides Harmonic Neutralization in Three-Phase, four-Wire Systems", IEEE-APEC Record 1993, pp 841-846.

[12]. M. Aredes and E. H. Watanabe, "New Control Algorithms for Series Shunt Three-Phase Four-Wire Active Power Filter", IEEE Transactions on Power Delivery, Vol.10, No.3, July 1995, pp1649-1656.

[13]. K. Haddad, T. Thomas, G. Joos and A. Jaafari, "Dynamic Performance of Three Phase Four Wire Active Filters", IEEE-APEC Record 1997, pp 206-212.

[14]. T. Furuhashi, S. Okuma and Y. Uchikawa, "A Study on the Theory of Instantaneous Reactive Power", IEEE Transactions on Industrial Electronics, Vol.37, No.1, Feb 1990, pp 86-90.

[15]. B. Singh, K. AL-Hadded and A. Chandra, "Active Filter with Sliding Mode Control", IEE Proceedings on Generation, Transmission and Distribution, Vol.104, No.6, Nov.1997.

[16]. C. A. Quinn and N. Mohan, "Active Filtering of Harmonic Currents in Three-Phase Four-Wire Systems with Three Phase, Single Phase Non-linear Loads", IEEE-APEC Record 1992, pp 829-836.

[17]. G. Kamath, N. Mohan and V. D. Albertson, "Hardware Implementation of a Novel Reduced Rating Active Filter for Three-Phase, Four-Wire Loads", IEEE-APEC Record 1995, pp 984-989.

[18]. H. Fujita and H. Akagi, "Unified Power Quality Conditioner: The Integration of Series Active Filter and Shunt Active Filter", IEEE-PESC Record 1996, pp 494-501.

[19]. M. Basu, "Some Investigation on Unified Power Quality Conditioner", Ph.D Thesis IIT Kanpur, June 2002.

[20]. M. Sri Balaji, "Utility Friendly Regenerative Magnet Load Power Supply", M.Tech. Thesis IIT Kanpur, 2002.

[21]. G. K. Dubey, S. R. Doradla, A. Joshi, and R. M. K. Sinha, "Thyristorised Power Controllers", New Age International Publishers, New Delhi, 2001.

[22]. P. Jaiswal, "Improved Utility Interface for ac Drive System with Voltage Sag Ride-Through Capability", M. Tech. Thesis IIT Kanpur, May 2003.

ANNEXURE – I

Some Additional Results

A. **Single phase APF** ($k_p = 1$, $k_i = 0.01$), V_S (peak) = 100 V, 50 Hz, $V_{dc}^* = 200$ V
Load: Single phase non-linear load (diode bridge rectifier).

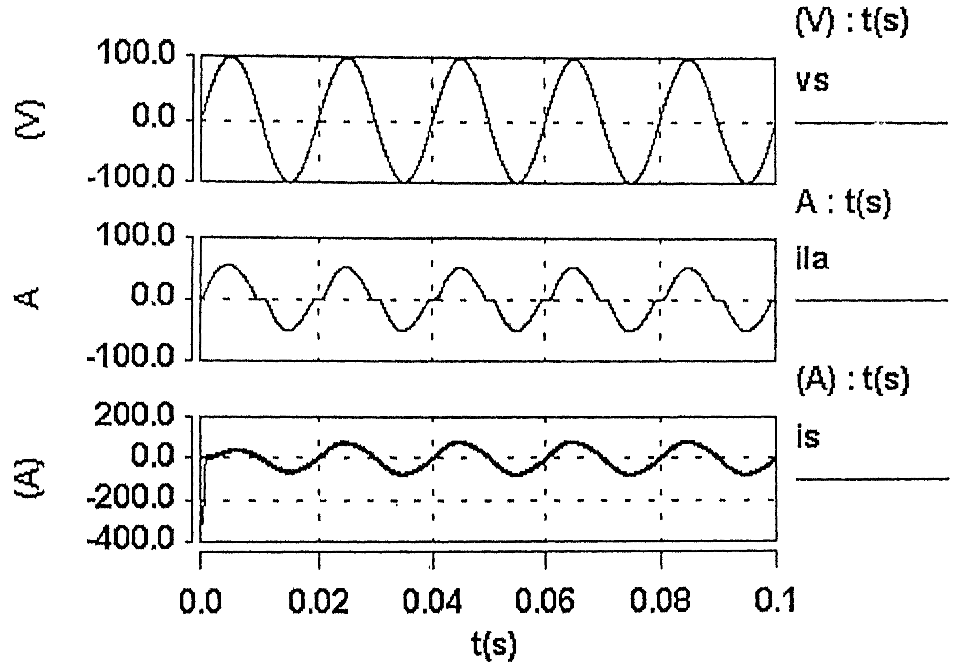

Fig. A.1 Supply voltage, current and load current

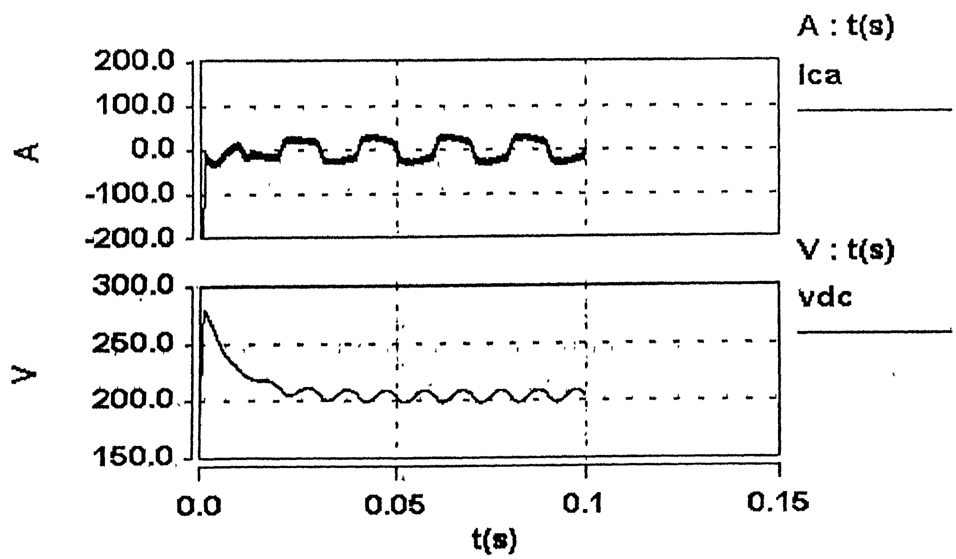

Fig. A.2 Compensating current and dc link voltage

B. Three phase three wire APF

($k_p = 1$, $k_i = 0.011$), V_{phase} (peak) = 50 V, 50 Hz, $V_{dc}^* = 180$ V

Load: Three phase non-linear load (diode bridge rectifier).

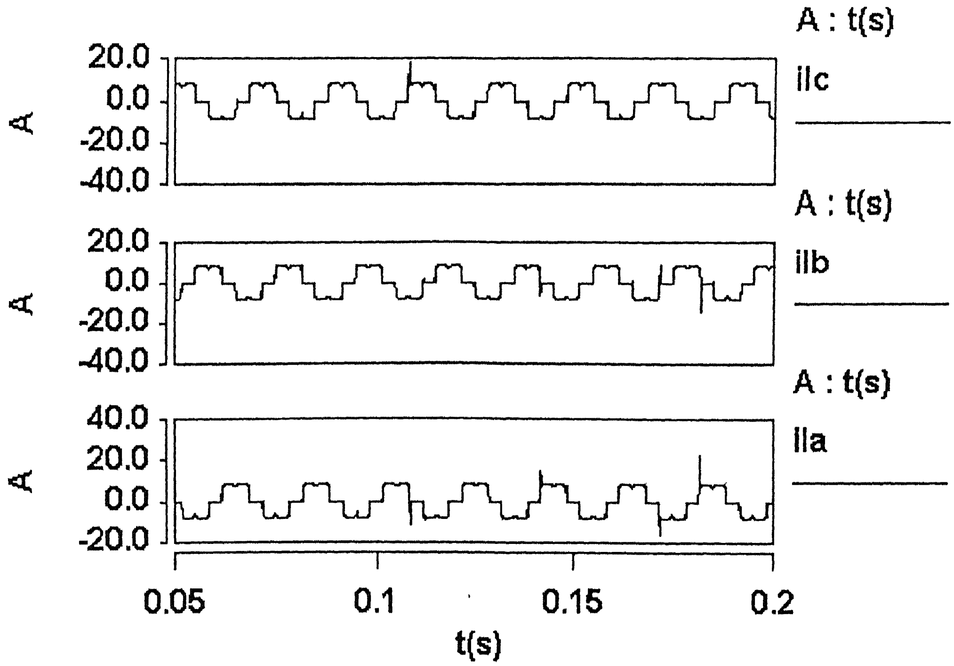

Fig. B.1 Three phase non-linear load currents

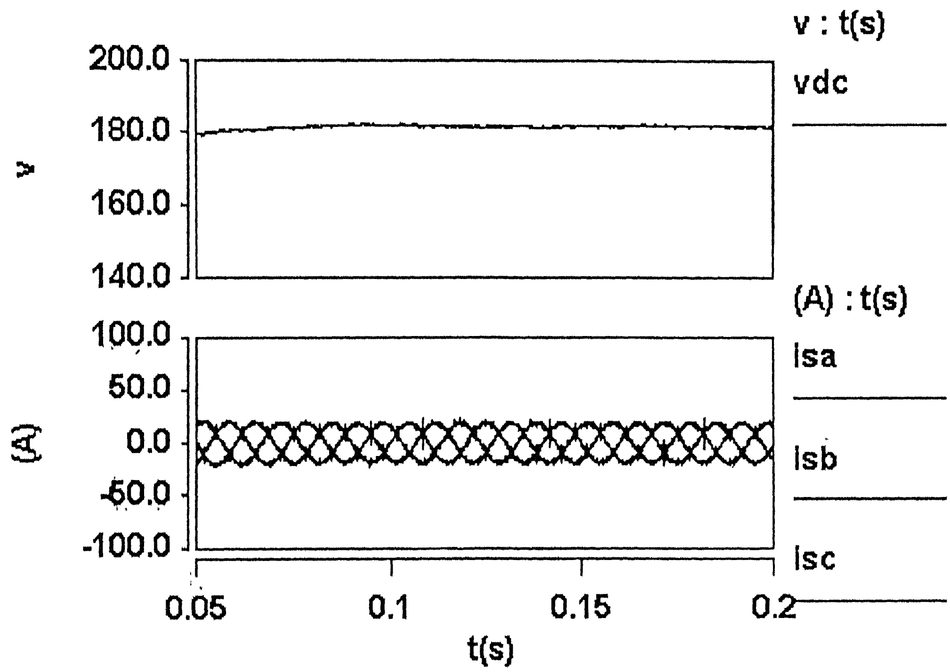

Fig. B.2 Source currents and dc link voltage

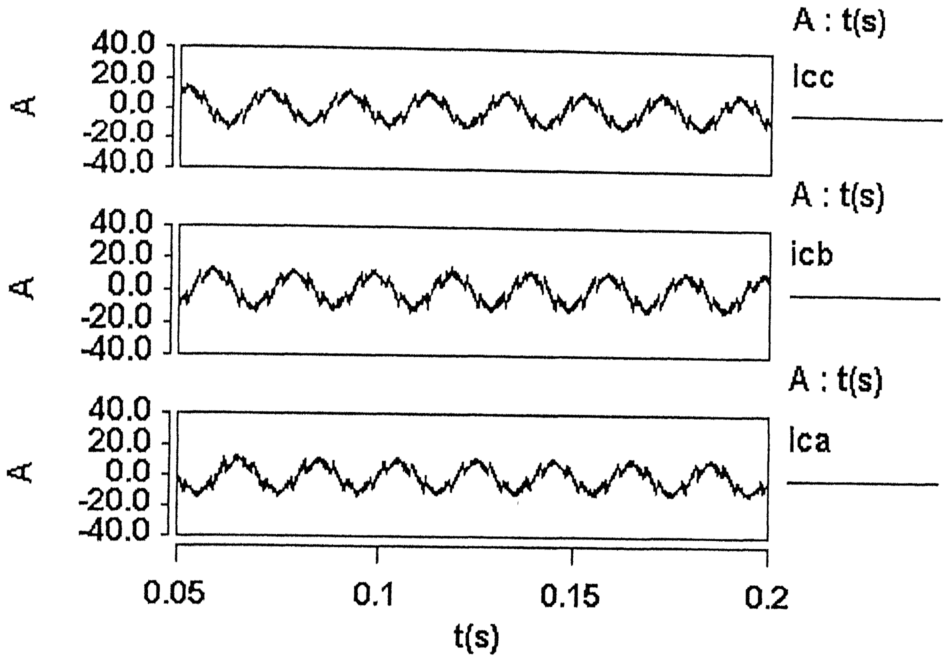

Fig. B.3 Compensating currents

C. **Three phase four wire (four leg inverter) APF**
($k_p = 1$, $k_i = 0.0108$), V_{phase} (peak) = 50 V, 50 Hz, $V_{dc}^* = 140$ V
Load: Three phase unbalance load.

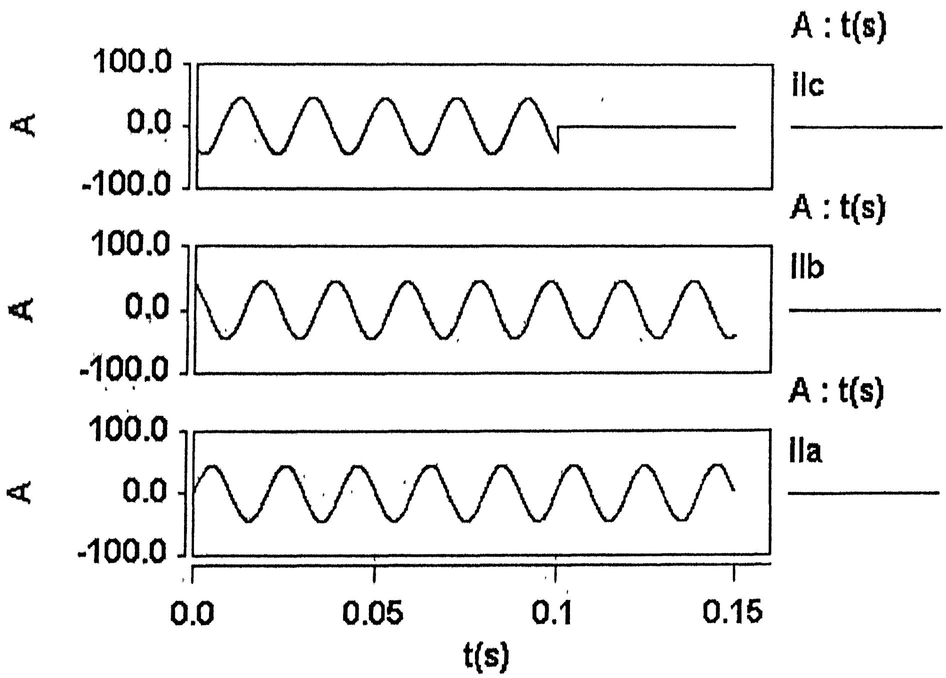

Fig. C.1 Three phase unbalance load currents

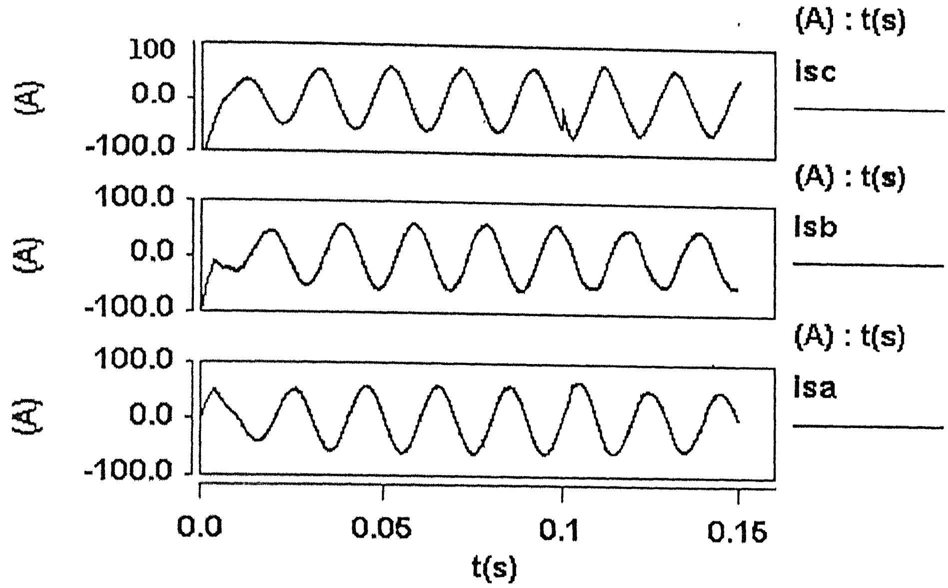

Fig. C.2 Source currents

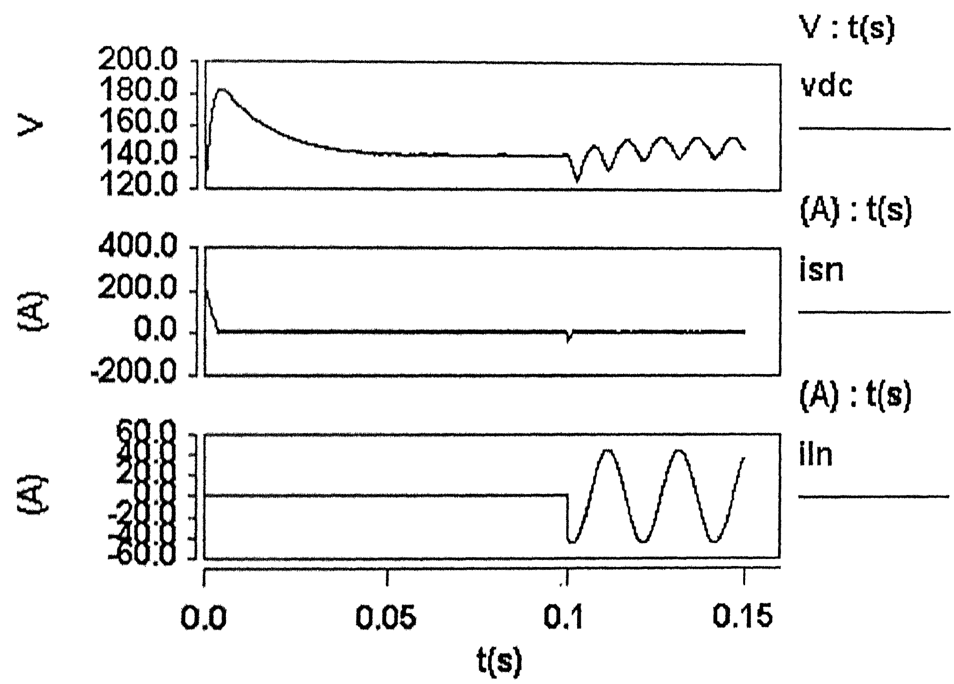

Fig. C.3 Neutral current of source side and load side, dc link voltage

D. Three phase four wire (Split capacitor) APF
($k_p = 1$, $k_i = 0.011$), V_{phase} (peak) = 50 V, 50 Hz, $V_{dc}^{*} = 140$ V
Load: Three phase non-linear load. (diode bridge rectifier).

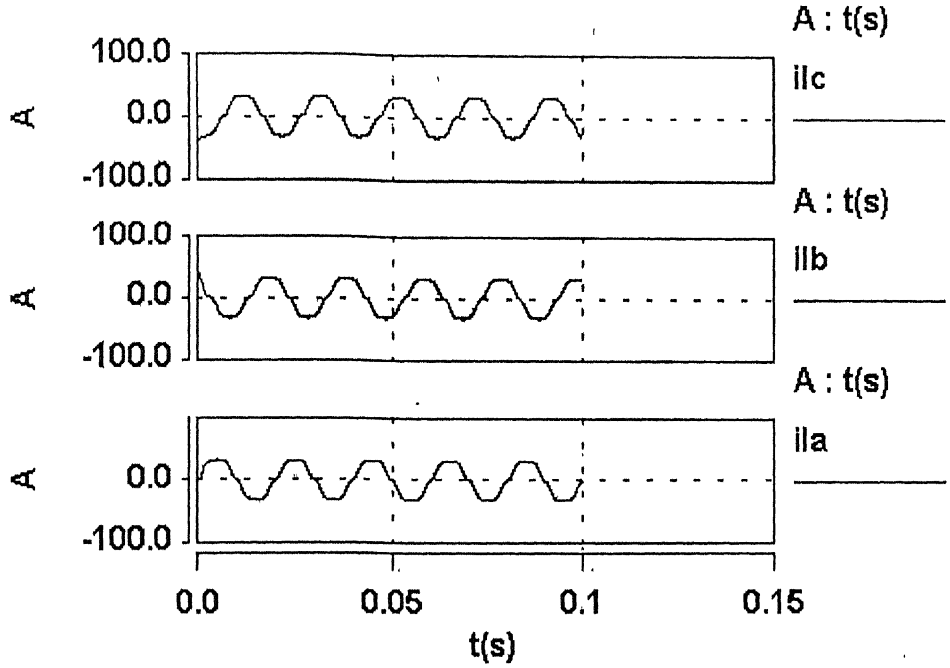

Fig. D.1 Three phase load currents

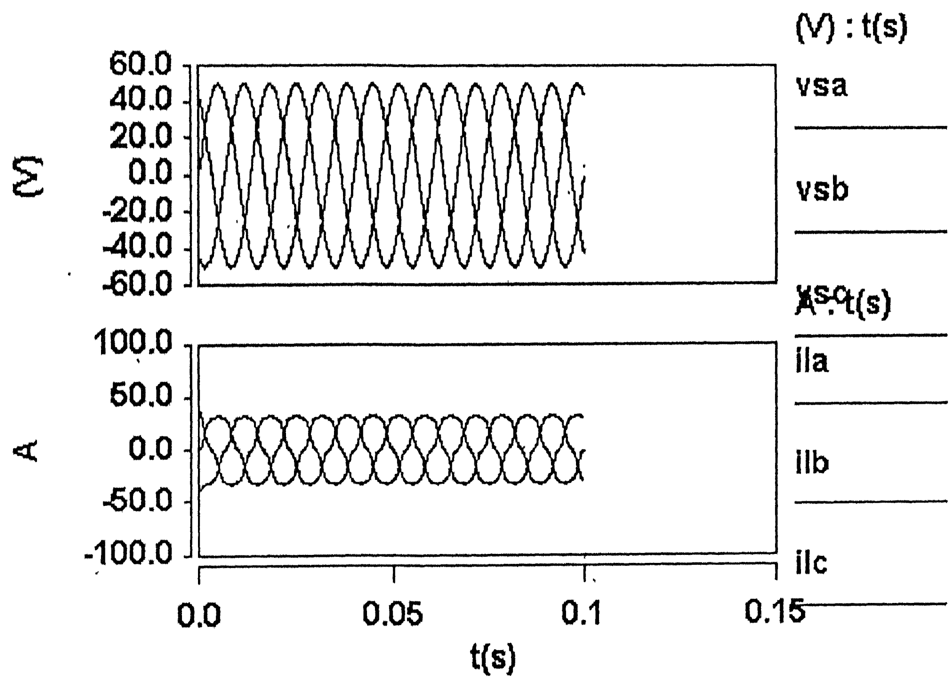

Fig. D.2 Source voltage and load currents

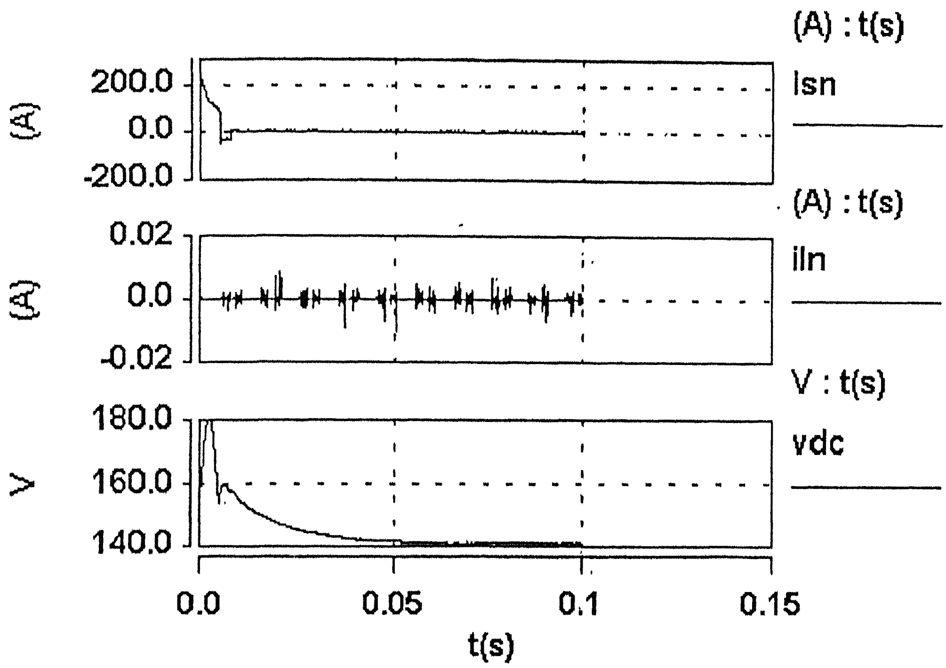

Fig. D.3 Neutral current of source side and load side, dc link voltage

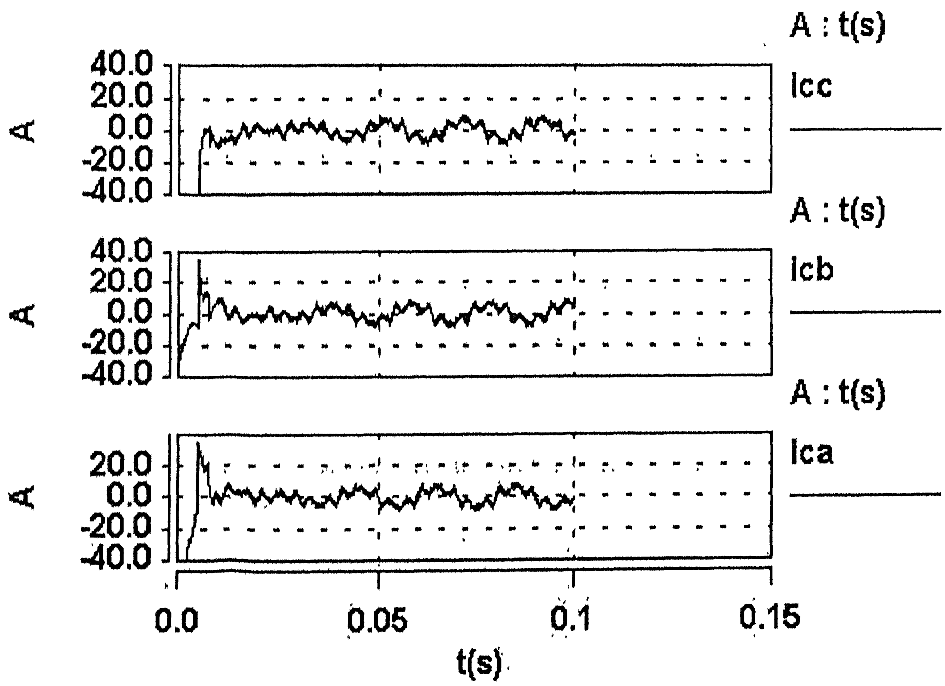

Fig. D.4 Compensating currents